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ELECTRIC POWER TRANSMISSION

A PRACTICAL TREATISE FOR PRACTICAL MEN

BY

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PREFACE.

THIS volume is designed to set forth in the simplest possible manner the fundamental facts concerning present practice in electrical power transmission.

Busy men have little time to spend in discussing theories of which the practical results are known, or in following the derivation of formulæ which no one disputes. The author has therefore endeavored, in introducing such theoretical considerations as are necessary, to explain them in the most direct way practicable; using proximate methods of proof when precise and general ones would lead to mathematical complications without altering the conclusion for the purpose in hand, and stating only the results of investigation when the processes are undesirably complicated.

In writing of a many-sided and rapidly changing art, it is impossible in a finite compass to cover all the phases of the subject or to prophesy the modifications that time will bring forth; hence the epoch of this work is the present and the point of view chosen is that of the man, engineer or not, who desires to know what can be accomplished by electrical power transmission, and by what processes the work is planned and carried out. This treatment is not without value to the student who wishes to couple his investigations of electrical theory with its application in the hands of engineers, and puts the facts regarding a very great and important development of applied electricity in the possession of the general reader.

Such apparatus as is described is intended to be typical of the methods used, rather than representative of any particular scheme of manufacture or fashion in design. These last change almost from month to month, while the general conditions remain fairly stable, and the underlying principles are of permanent value.

L. B.

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ELECTRIC TRANSMISSION OF POWER.

CHAPTER I.

ELEMENTARY PRINCIPLES.

It has long been the fashion to speak of what we are pleased to call electricity as a mysterious "force," and to attribute to everything connected with it occult characteristics better suited to mediæval wizardry than to modern science. This unhappy condition of affairs has, in the main, come about through the indistinctness of some of our fundamental ideas and inexactitude in expressing them.

To speak specifically, there has been, even in the minds and writings of some who ought to know better, a tendency toward confusing the extremely hazy individuality of "electricity" with the sharply defined properties of electrical energy. We have been so overrun by theories of electricity, two-fluid, one-fluid, and non-fluid, with electrically "charged" atoms and duplex ethers, that we have well-nigh forgotten the very great uncertainty as to its concrete existence. Even admitting it to be an entity it most assuredly is not a force mysterious or otherwise. Electrical force there is, and electrical energy there is, and with them we can freely experiment, but for most practical purposes "electricity" is merely the factor connecting the two. It is related to electrical energy just as that other hypothetical fluid "caloric" was supposed to be related to heat energy. The analogy is not absolutely exact, but it nevertheless expresses the facts in the case.

The day has passed wherein we were at liberty to think of "electricity" as flowing through a material tube or as plastered upon bodies like a coat of paint. The things with which

we have now to deal are the various factors of electrical energy.

It is the purpose of this chapter to treat of that form of energy which we denominate electrical, to discuss its relation to other forms of energy and some of the transformations which they may reciprocally undergo.

Speaking broadly, *energy* is power of doing work. The energy of a body at any moment represents its inherent capacity for doing work of some sort on other bodies. This, however, must not be understood as implying that the aforesaid energy is limited by our power of utilizing it. We may or may not be able to employ it to advantage or under possible conditions. As an example take the massive weight of a pile driver. Raised to its full height it possesses a certain amount of gravitational energy—a possibility of doing useful work. This energy is temporarily unemployed and appears only as a stress on the supporting rope and frame-work. Under these circumstances, wherein the energy exists in static form, it is generally known as *potential* energy.

Now let the weight fall and with swiftly gathering velocity it strikes the pile and does work upon it, settling it deep into the mud. The energy due to the blow of the *moving weight*, energy of motion in other words, is called *kinetic*. But at the bottom of its fall the weight still has potential energy with reference to points below it, and we realize this as the pile settles lower and each successive blow becomes more terrific. At some point we are unable further to utilize the fall, and have then reached the limit of the *available* energy in this particular case.

We must not forget, however, that each time the weight was lifted, work had to be done against gravitation to give the weight its point of vantage with respect to available energy. This work was probably done by utilizing the energy of expanding steam—in other words, the energy of the steam was transformed through doing work on the piston into kinetic energy of the latter, which, through doing work against gravitation, has been enabled again to reappear as the energy of a falling body, and to do work on the driven pile. And back of the steam energy is the heat energy, by which work is done on the water in the boiler, and yet back of this the

chemical energy of the coal transformed into heat energy and doing work on the minute particles of iron in the boiler, for we know that heat is a species of kinetic energy.

Even the work done on our pile is not permitted to go untransformed into energy. Part is transformed into heat energy through friction and compression of the pile, part through friction of the water, and part into tiny waves that may lift against gravity chips and pebbles on a neighboring shore. Other fractions go into the vibrational energy of sound, into heating the weight so that it gives out warmth—radiant energy—to the hand when held near it, and to the surrounding air, and into electrical work done on the weight and neighboring objects, for the weight unquestionably receives a minute amount of electrical energy at each blow. Thus a comparatively simple mechanical process involves a long series of transformations of energy.

No energy is ever created or destroyed, it merely is changed in form to reappear elsewhere, and work done is the link between one form of energy and another. And we may lay down another law of almost as serious import: *No form of energy is ever transformed completely into any other.*

On the contrary the general rule is that with each transformation several kinds of energy appear in varying amounts, and among them we may always reckon heat. The object of any transformation is usually a single form of energy, hence practically no such thing as perfectly efficient transformation can be obtained. The energy by-products for the most part cannot be utilized and are frittered away in useless work or in storing up kinds of potential energy that cannot be employed.

The greatest loss is in heat, which is dissipated in various ways and cannot be recovered. Heat is therefore generally the worst enemy of efficiency.

From what has gone before we can readily appreciate that when we do work with the object of rendering available a particular kind of energy, the method must be intelligently selected, else there will result useless by-products of energy which will seriously lower the efficiency of the operation.

Whenever possible we utilize potential energy already existing in securing a transformation. Thus if heat is wanted, the easiest way of getting it is to burn coal, and to allow its energy to become kinetic as heat. If we want mechanical work done,

we set heat energy to work in the most efficient way practicable. If electrical energy is desired we set the energy of steam to revolving the armature of a dynamo. If the right method of transformation is not taken, much of the energy will turn up in forms that we do not want or cannot utilize. Burning coal is a very bad way of getting sound, just as playing a cornet is but a poor means of getting heat, although a fire does produce a trifling amount of sound, and a cornet by continual vibration must be warmed to a minute degree.

These seem, and perhaps are, extreme instances, but when we realize that, somewhat to the discredit of human ingenuity, less than one-twentieth of the electrical energy supplied to an incandescent lamp appears in the form of light, the comparison becomes grimly suggestive.

Understanding now that in order to obtain energy in any given form (such as electrical) particular methods of transformation must be used in order to secure anything like efficiency, we may look a little more closely at various types of energy to discover the characteristics that may indicate efficient methods of transformation, particularly as regards electrical energy.

Speaking broadly, one may divide energy into three classes:

1st. Those forms of energy which have to do with movements of, or strains in, masses of matter. In this class may be included the ordinary forms of kinetic energy of moving bodies and the like.

2d. Those which are concerned with movements of, or strains in, the molecules and atoms of which material bodies are composed. In this class we may reckon heat, latent and specific heats, energy of gases and perhaps chemical energy.

3d. All forms of energy which have to do with strains which can exist outside of ordinary matter, *i. e.*, every kind of radiant energy and presumably electrical energy.

These classes are not absolutely distinct; for example, we do not know the relation of chemical energy to the third class, nor of gravitational energy to any class, but such a division serves to keep clearly in our minds the kind of actions to which our attention is to be directed.

It is only within the past few years that we have been able with any certainty to classify electrical energy, and even now much remains to be learned. For a very long while it has

been known that light, *i. e.*, luminous energy, must be propagated through a medium quite distinct from ordinary matter and possessing certain remarkable properties. It was well known that luminous energy is transferred through this medium by vibratory or wave motion. Even the period of the vibrations and the lengths of the waves were accurately measured, and from these and similar measurements it has been possible to classify the mechanical properties of this medium, universally called "the ether," until we really know more about them than about the properties of many kinds of matter—a number of the rare metals for example.

The next important step was the discovery, verified in the most thorough manner, that what had been known as radiant heat, such as we get from the sun or any very hot body, is really energy of the same kind as light. That is, it was found, to be energy of wave motion of precisely the same character and in the same medium, differing only in frequency and wave length. It also has turned out in similar fashion that what had been called "actinic" rays, that are active in attacking a photographic plate and producing some other kinds of chemical action, are only light rays of shorter wave length than usual, and so ordinarily invisible to the eye.

So much having been ascertained it became clear that instead of three kinds of energy—"heat, light and actinism," we were really dealing with only one—radiant energy, vibrating energy in the ether, varying in effect as it varies in frequency. Speaking in an approximate way, such wave energy has a frequency of *six hundred thousand billion* vibrations per second and a velocity of propagation of about a hundred and eighty-five thousand miles per second, so that each wave is not far from one fifty-thousandth of an inch long. These dimensions are true of light waves; chemical action can be produced by waves of half the length, while so called heat rays may be composed of waves two or three times as long as those of light. Such figures are startling, but they can be verified with an accuracy greater than that of ordinary mechanical measurements.

We see that this radiant energy is capable of producing various disturbances perceptible to our senses, such as chemical action, light and heat, and that these different effects

simply correspond to waves of energy having different frequencies and wave lengths. This being so, it is not unnatural to suppose that at still different frequencies other effects might be noted. This idea gains further probability from the experimental fact that waves of very different frequencies traverse the ether with precisely the same velocity, showing no signs of slowing down or dying out, so that there seems to be no natural limit to their length.

During the past half dozen years it has been clearly shown that "radiant energy" is capable of producing profound electrical disturbances, such as violent oscillations of electrical energy in conducting bodies, and that these effects exist whatever the frequency of the ether waves concerned. This very important fact was clearly foreseen by Maxwell more than twenty years ago, regarding light, and his prediction has been thoroughly verified through the persistent researches of the late Professor Hertz and others.

This discovery is often expressed by saying that radiant energy is an electro-magnetic disturbance, or that light is one kind of electrical action. It is more strictly accurate to say that radiant energy, just as it produces chemical disturbances on the photographic plate, affects the eye as light, and material bodies as heat, is also capable of producing electrical effects when transferred to the proper media. Most of our experiments on its electrical effects have been performed with waves many thousand times longer than those of light, but their general character has proved to be exactly the same.

A given substance may be differently related to waves of radiant energy of different lengths, but the phenomena are still essentially the same. For instance, a plate of hard rubber is thoroughly opaque to waves of a length corresponding to light, but is quite transparent to those of considerably greater length, such as can produce thermal or electrical effects. A plate of alum will let through light waves and very long waves, but will stop most of those which are efficient in producing heat. A thick sheet of metal is quite opaque to all known waves of radiant energy. Hence, the fact noted long ago by Maxwell, that all good conductors are opaque to light, although the converse is not true.

The substance of all this is, that the same sort of disturb-

ance in the ether which produces light is also competent to set up electrical actions in material bodies, and conversely, such actions may and do produce corresponding disturbances in the ether which are thus transferred to other bodies. Such a transference corresponds to all that we know concerning the velocity with which electrical and electro-magnetic disturbances pass from body to body. It is equally certain that this velocity totally transcends anything we could hope to obtain from bodies having the dynamical properties of ordinary matter, while it does fit exactly the dynamical properties of the ether.

We are thus forced to the conclusion that when an electrical current, as we say, "passes along" a wire, whatever a "current" may be, it is not simply passed along from molecule to molecule in the wire as sound or heat would be, but that there is an immensely rapid transfer of energy in the neighboring ether that reaches all points of the wire almost simultaneously. It takes a measurable time for the electrical energy to reach and utilize the centre of the wire although its progress over the surface, thanks to the free ether outside, is enormously rapid.

Thus takes place what is generally called a "flow of electricity" along the wire. Looking at the process more closely, the nearest approach to flow is the transfer of energy along the wire by means of stresses in the ether which set up strains in the matter along their course.

Whenever we cause in matter the particular stress which we call electromotive force for lack of a more exact name, the resulting strain is electrification, and if the stress be applied at one point of a conducting body, the strain is immediately transferred to other points by the stresses and strains in the surrounding ether. Wherever this transference of strain exists we have an electrical current, although this name is generally reserved for those cases in which there exists a perceptible transference of energy by the means aforesaid. If the conditions are such that energy must be steadily supplied to keep up the electromotive stress we have such a state of things as we find in a closed circuit containing a battery.

To cause such a flow of energy we must first find means of setting up electromotive stress capable of being propagated through the ether. Now atoms and molecules are the only

handles by which we can get hold of the ether. In so far as we can work on them we can do work on the ether.

As a matter of fact we cannot do work of any kind on the molecules of a body without setting up electrical stresses of some sort. In most cases of mechanical work, which in the main produces stress on the molecules only by strains in the mass, the energy appears mainly as heat, and is only incidentally electrical, as for instance the energy wasted in a heated journal.

When, however, by any device we do work more directly on the molecules of a body, or on the atoms which compose the molecules, we are more than likely to transform much of this work into electrical energy. As a rough example of the two kinds of action just mentioned, pounding a body heats it without causing any considerable electrification, while on the other hand rubbing it rather gently, sets up a considerable electrification without heating it noticeably.

In fact, for many centuries, friction was the only known method of causing electrification. Later, as is well known, it was discovered that certain sorts of chemical action, which has to do directly with interchanges of energy between molecules, were very potent in electrical effects. With this discovery came the ability to deal with steady transfers of electrical energy in considerable amount (electric currents), instead of the relatively slight and transitory effects previously known (electrification, "frictional" electricity).

To clear up the real nature of this difference it is well to consider what we mean by saying that a body is electrified, or has an electrical charge. In other words, what is electrification? Not very many years ago this question would have been answered by saying that a quantity of a substance, positive electricity (or negative as the case might be), had been communicated to the body in question; that this remarkable substance could reside only at the surface of the body and was able to produce in surrounding bodies exactly an equal quantity of negative electricity; that this "charge" of electricity would repel another "charge" of the same substance placed near it, or attract a charge of its opposite, the other substance called negative electricity; and much more to the same effect. All this was a very convenient hypothesis—it

explained, after a fashion, the common facts and enabled investigators to discover many important electrical relations and laws. But it expressed much more than there was any reason to know. From the standpoint of our modern doctrines of energy electrification is a very different thing.

Let an electromotive stress (from whatever source) be applied to a body, a metallic sphere for example, long enough to transfer to it a finite amount of energy. This energy appears as stresses and strains in the ether everywhere about the body under consideration and thence extends to the molecules and atoms of neighboring bodies, causing "induced charges." It is as if one were to fill a box with jelly, and then pull or push or twist a rod embedded in its centre. The result would be strains in the rod, the jelly and the box, and in a general way the total stress on the box would equal that on the rod. By proper means we could detect the strain all through the substance of the jelly, but most easily by its variations from place to place.

We do not know exactly what sort of a strain in our ether jelly is produced by electromotive stress, but we do know that it possesses the quality of endedness, so that the strains in the matter concerned, *i. e.*, in the ball and surrounding bodies, are equal and opposite.

In fact the two "charges" are merely the two ends of the same strain in the ether. They appear to us to be real attributes of the two opposed surfaces, because at these surfaces the dynamical constants, such as density, elasticity, etc., of the medium through which the strain is propagated, change in value, and differences in state of strain there become plainly manifest.

In electric currents we have a very different state of things. The energy supplied by the electromotive stress, instead of becoming potential as electrostatic strain, does work and is transformed into other kinds of energy, thermal or chemical, mechanical or luminous.

When a stress of whatever kind is applied to a body, only a limited amount of energy can be transferred by it so long as the energy remains potential. Thus in our box of jelly before referred to, a twist of given intensity applied to the stick, as for instance by a string wound around it and pulled by a given

weight, can only transfer energy until the stresses produced in the jelly come to an equilibrium with it. On the other hand if the box were filled with water and the stick were the axle of a sort of paddle wheel, the very same intensity of twist could go on communicating energy to the water as long as one chose to apply the necessary work.

This roughly expresses the difference between electric charge and electric current, viewed from the standpoint of energy. An electromotive stress applied to a wire *charges* it and then the transfer of energy ceases. If the same stress be applied under conditions that allow work to be done by it, energy will be transferred so long as the stress is kept up. In an open electric circuit we have a charge as the result of electromotive stress. When the circuit is closed, *i. e.*, when a continuous medium is furnished on which work can be done, we have an electric current. The amount of this work and the flow of electrical energy that produces it, depend on the nature of the circuit. Certain substances, especially the metals, and of metals notably copper and silver, permit a ready continuous transfer of energy in and about them. Such substances are called good conductors. The real transfer of energy takes place ultimately *via* the ether, but its amount is limited by the amount and character of the matter on which work can be done.

Whenever the strains in the ether, such as we recognize in connection with electrical charge, shift through space as when a current is flowing, other strains bearing a certain relation to the direction of flow are made manifest. Where there is a rapid and intense flow of energy these strains are very great and important compared with any electrostatic strains that exist *outside the conducting circuit.* In other cases they may be quite insignificant. These strains are electro-magnetic, and with them we have to do almost exclusively in practical electrical engineering. They appear wherever there is a moving electrical strain, whether produced by moving a charged body or causing the charge upon a body to move.

Both kinds of strains exist in radiant energy, as in other cases of flowing energy. The stresses in electro-magnetic energy are at right angles both to the electrostatic stresses and to the direction of their motion or flow. If for example

we have a flow of electrical energy in a straight wire (Fig. 1), the electro-magnetic stresses are in circles about it.

If *A* be a wire in which the flow of energy is straight down into the paper the electro-magnetic stresses are in circles in the direction shown by the arrow heads. If the wire be bent into a ring (Fig. 2), with the current flowing in the direction of the arrows, then the electro-magnetic stresses will be (following Fig. 1) in such direction as to pass downward through the paper inside the ring.

These electro-magnetic stresses constitute what we call a *magnetic field* outside the wire. The intensity of this field can be increased by increasing the flow of energy in the desired

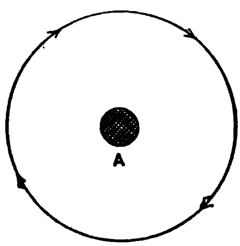


FIG. 1.

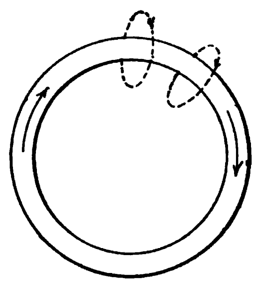


FIG. 2.

region in the systematic way suggested by Fig. 2. If, for example, we join a number of rings like Fig. 2 into a spiral coil shown in section in Fig. 3, in which the current flows downward into the paper in the lower edge of the spiral, there will be produced a magnetic field in which the stresses have the direction shown by the arrows. Such a spiral constitutes a genuine magnet, and if suspended so as to be free to move would take up a north and south position with its right-hand end toward the north. In and about the spiral there exists a magnetic "field of force," which is merely another way of saying that the ether there is under electro-magnetic stress. Its condition of strain is closely analogous to that about an electrified body, and, as in that case, there is no work done on the ether after the strains are once established. While this is being accomplished work is done just as when a body is charged.

If now setting up such an electro-magnetic field requires energy to be spent by causing a current to flow in the spiral, we should naturally expect that if the same field could be set up by extraneous means, energy would momentarily be spent on the spiral in producing stresses and strains similar to those

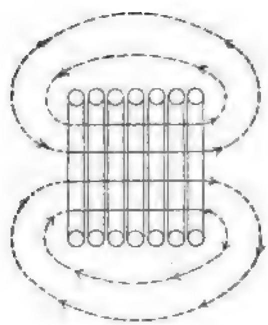


FIG. 3.

that set up the original field. This is found to be so, the process working backward as well as forward.

If, for example, we have two rings (Fig. 4), and by sending a current around one, transfer energy to the medium outside it, this energy will set up an electromotive stress in the other

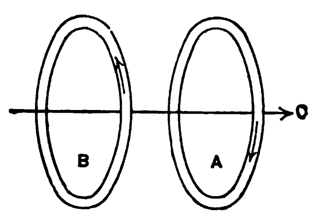


FIG. 4.

ring. The direction of this stress is not at once obvious, but we can get a very clear idea of it by considering the work done. If current is started in *A* (Fig. 4), in the direction shown, electro-magnetic stresses are produced in the direction of the arrow *C*. If these are to do work on *B*, the electromotive stress in the latter cannot have such a direction as to set up on its own account a magnetic field that would *assist*

that of *A*, otherwise we could increase the field indefinitely without added expenditure of energy. Therefore the electromotive stress in *B*, and hence the current, must be in a direction opposing the original current in *A*, as shown in the figure.

In like manner if the current in *A* be stopped and the field due to it therefore changes, there are changes in the electromagnetic stresses about *B*, that again set up an electromotive stress in it. If, however, this change of stress is to do work, the electromotive stress in *B* must be of such direction as to oppose by its field the change in the field of *A*—*i. e.*, it must change its direction and will now give us a current in the same direction as the original one in *A*. All this follows the general law, that if work is to be done by any stress it must be against some other stress. There can be no work without resistance.

In Fig. 4 we have the fundamental facts of current induction on which depend most of our modern methods of generating and working with electrical energy. Summed up they amount to saying that whenever there is a change in the electromagnetic stresses about a conductor, work is done upon it, depending in direction and magnitude on the direction and magnitude of the change in the stresses.

This is equally true whether the stresses change in absolute value or whether the conductor changes its relation to them. Thus in Fig. 4, if *A* carries an electrical current the result on *B* is the same whether the field of *A* changes through cessation of the current, or whether the same change in the stresses about *B* is produced by suddenly pulling *B* away from *A*. The rate at which work is done depends on the rate at which the stresses are caused to change, as might be expected. So long as the stresses are constant with reference to the conductor in which current is to be induced, no work can be done upon it.

These principles form the foundation of the dynamo, motor, alternating current transformer and many other sorts of electrical apparatus. Their details may differ very widely, but we can get all the fundamental ideas from a consideration of Figs. 3 and 4. To somewhat define the specific idea of the dynamo, consider what happens when a conducting wire is thrust into a magnetic field such as is produced by a coil, as in Fig. 5. As in Fig. 3, let the current in the coil be flowing down-

ward into the paper in the lower half of the figure. *A* is a wire perpendicular to the plane of the paper in front of the coil, its ends being united at any distant point that is convenient. Knowing that moving the wire into the field will set up electromotive stresses in it, we can as before determine

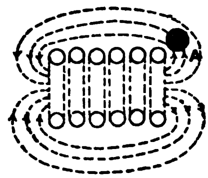


FIG. 5

their direction by remembering that work must be done. That is (see Fig. 1), the induced current will flow through *A* downward into the paper. In passing out of the field the current would be upward.

We have so far neglected the rest of the circuit. To be exact we should consider it as in Fig. 6. Following the same line of reasoning as in Fig. 5, we see that while the ring *A* is entering the magnetic field the current induced in it must be opposite to that in the inducing coil (see Fig. 4). When the

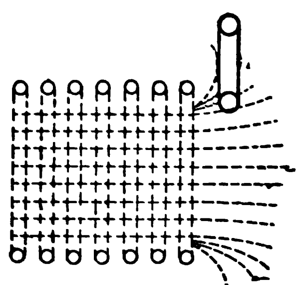


FIG. 6.

coil is leaving the field, however, this direction will be reversed. Considering the coil *A* as a whole, we see that so long as the total field tending to set up stresses in it is *increasing*, a current will be induced opposed to that in the inducing coil. While the total field is diminishing, the induced current will be in the other direction. The work that is spent in

moving the coil *A* will for the most part reappear as electrical energy in that coil. Arrange the parts of Fig. 6, so that the motion of *A* can be accomplished uniformly and continuously and we should have a true, though rudimentary, dynamo. Such a structure could be made by fixing *A* to the end of an arm pivoted at the other end and then revolving the arm so that at each revolution the coil *A* would sweep through the field of the magnetizing coil (see Fig. 7). The result of this, as we have seen, would be on entering the field a current in one direction, and on leaving, a current in the other. There

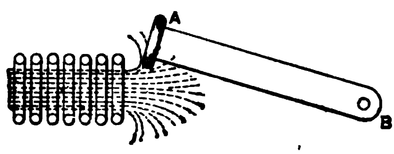


FIG. 7.

would thus be an alternating current developed in the ring *A*. If it were cut at some point and wires led down the arm and to two metal rings on the axis *B* we could obtain, by pressing brushes on these rings, an alternating current in any outside circuit. To make more of the revolution of the arm useful we could arrange inducing coils in a circle about *B*. There would then be an alternation as *A* passed each coil.

All these devices, however, would produce comparatively weak effects, because it is difficult to produce powerful magnetic stresses in so simple a way. There are very few materials in which magnetic stresses are easily set up or propagated. Chief among these is iron, which bears somewhat the same relation to magnetic actions that copper does to electrical ones. By giving to the coil in Fig. 7 a core of soft iron the electromagnetic effects obtained from it would be greatly enhanced. They are comparatively feeble in air and the more iron we put in their path the better. Developing this idea we have in Fig. 8 a much better device for setting up electric currents. Here the coil of Fig. 7 is wound around an iron core the ends of which are brought near together. The arm of Fig. 7 is also of iron with enlarged ends and the ring *A* is replaced by a coil of several turns.

The magnetic stresses brought to bear on the coil *A* are thus made comparatively powerful. Following out on Fig. 8 the reasoning applied to Fig. 7, we see that considerable electromotive stresses would be set up by the revolution of *A*, alternating in direction at each half revolution. In fact *A* is the armature of a simple alternating dynamo, having two poles *N* and *S*, so called from their magnetic relations (see Fig. 3).

We have not thus far considered the source of the electromagnetic field involved. It may be obtained as shown by utilizing the electro-magnetic stresses set up by a wire convey-

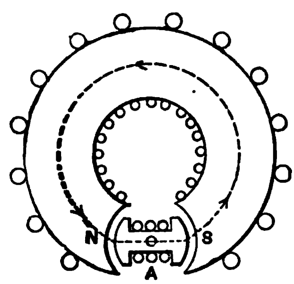


FIG. 8.

ing electrical energy or on a small scale from permanent magnets. The essential fact, however, is that by forcing a wire through a region of electro-magnetic stress, electromotive stresses are set up in that wire, the action in every case being in such direction as to compel us to do work on the wire. This work appears as electrical energy in the circuit including the moving wire.

Now return to Fig. 5 and consider the effect if the wire *A* is carrying a steady flow of electrical energy. It will set up electro-magnetic stresses about it as already described. If the current be downward into the paper in *A* these stresses will be opposed to the stresses in the field. Inasmuch as we have seen that in setting up such a current work had to be done in forcing the wire into the field, it follows that given such a current, there must be between its field and that of the coil a repulsive force which had to be overcome by doing the work aforesaid. In other words, there must have been a tendency to throw *A* out of the field of the coil. Just as

work had to be spent to produce electrical energy in *A*, so electrical energy will be spent in keeping up the stresses around *A* that tend to drive it out of the magnetic field. If the current in *A* were in the other direction the stresses in its field and that of the coil would be concurrent instead of opposed and their resultant would tend to draw wire and coil together, *i. e.*, work would have to be spent to keep them apart. This is the broad principle of the electric motor. It is sometimes referred to as simply a reversal of the dynamo, but it really makes no difference whether the structure in which the action just described takes place is well fitted to generate current or not. Given a magnetic field and a wire carrying electrical energy, and there will be a force between them depending in direction on the directions of the electro-magnetic stresses belonging to the two. If either element is arranged so as to move and still keep up a similar relation of these stresses we have an electric motor. Whether so arranged as to fulfill this condition with alternating currents, or in such manner as to require currents in one direction only, the principle is the same.

So far as unidirectional or "continuous" currents are concerned they are usually obtained from dynamo electric machines similar in principle to Fig. 8. This machine, if the ends of the winding on the armature be connected to two metal rings insulated from each other, serves as a source of alternating currents which can be taken off the two rings by brushes pressed against them. If it is necessary to obtain currents in one direction only, this can be readily done by reversing the connection of the outside circuit to the windings at the same moment that the current reverses in them. The simplest way of doing this is by a "two part commutator," such as is shown in diagram in Fig. 9. Here *A* is the shaft surrounded by an insulating bushing. On this are fitted two half rings *C* and *C'*, of metal (the commutator segments). On these bear brushes *B* and *B'*. If the ends of the winding are connected to *C* and *C'* and the brushes are so placed that they pass from one segment to the other at the moment when the current in the winding changes its direction, the direction of the current with respect to the brushes and the outside circuit with which they are connected obviously remains constant.

In the actual practice of dynamo building very many refinements have to be introduced to serve various purposes, but the underlying principle remains the same, *i. e.*, to set up in a conductor electromotive stresses by dragging it into and out of the strained region of ether under an electro-magnetic stress.

According as the dynamo is intended for producing continuous or alternating currents its structure is somewhat modified with its particular use in view. These modifications extend not only to the general arrangement but to the details of the winding. Alternating dynamos usually have a more com-

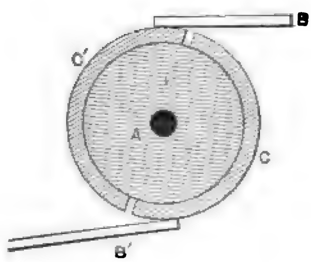


FIG. 9.

plicated magnetic structure than continuous current machines, and are almost invariably separately excited, *i. e.*, have their magnetizing current supplied from a generator specialized for producing continuous current. The magnetic complication is really only apparent, as it consists merely of an increased number of magnet poles, due to the desirability of obtaining tolerably rapid alternations of current.

Dynamos designed for producing continuous current are modified with the armature as a starting point. The winding is very generally much more complicated than that of an alternator and the commutator that serves to reverse the relation of the windings to the brushes at the proper moment is correspondingly elaborate. The magnetic structure is usually comparatively simple. The whole design is necessarily subordinated to securing proper commutation. Continuous current dynamos are almost universally self-excited, that is the current which magnetizes the field is derived from the brushes of the machine itself. Whatever the character of the machine the electromotive force generated in it increases with the inten-

sity of the magnetic field (that is, with the magnitude of the electro-magnetic strains which affect the armature conductors), with the speed (that is, with the rate of change of electro-magnetic stress about these moving conductors) and with the number of turns of wire of which the electromotive forces are added. The capacity of the machine for furnishing electrical energy varies directly with the electromotive force and with the capacity of the armature conductors for transmitting the energy without becoming overheated. Practically all the energy lost in a dynamo appears in the form of heat, which must be limited to an amount which will not cause an undue rise of temperature.

It is not the purpose of this chapter to deal with the practical details of dynamo design and construction. For these, the reader should consult special treatises on the subject, which consider it with a fullness which would here be quite out of place. Special machines, however, will be briefly discussed in their proper places and in relation to the work they have to do.

Having now considered the principles which underlie the transformation of mechanical into electrical energy, we may profitably take up the fundamental facts in regard to the measurement of that form of energy and the units in which it and its most important factors are reckoned.

All electrical quantities are measured directly or indirectly in terms of the dynamical units founded upon the units of length, mass and time. These derived dynamical units can serve alike for the measurement of all forms of energy so that all have a common ground on which to stand. As the electrical units are derived directly from the same units that serve to measure ordinary mechanical effects, electrical and mechanical energies are mutually related in a perfectly definite way.

A natural starting point in the derivation of a working system of electrical units may be found in electro-magnetic stress, such as is developed about an electrical circuit or a permanent magnet. To begin with, the mechanical units that may serve to measure any form of energy are derived from those of length, mass and time. These latter are almost universally taken as the centimetre, gramme and second, the "C. G. S."

system. Starting from these the unit of force is that which acting for one second on a mass of one gramme can change its velocity by one centimetre per second. This unit is called the *dyne* and as a magnetic stress it is equivalent to a push of about $\frac{1}{445,000}$ of a pound's weight on a similar "unit pole" one centimetre distant. This unit is inconveniently small for practical use and before long some multiple of it is likely to be given a special name and used for practical reference. In fact, one *megadyne* (*i. e.*, 1,000,000 dynes) is very nearly equivalent to the weight of a kilogramme. Magnetic measurements may thus be made by direct reference to the dyne and centimetre, since the unit pole is that which repels a similar pole 1 cm. distant, with a force of 1 dyne.

Referring now to what has been said about the causes which vary the electromotive force produced in a dynamo, we fall at once into the definition of the unit electromotive force, which is that produced when field, velocity, and length of wire under induction are all of unit value. The unit electromotive force is, then, that which is generated in one centimetre of wire moving one centimetre per second, perpendicular to its own length, straight across unit field, which is that existing one centimetre from unit pole as indicated above. This unit, too, is inconveniently small, so that one hundred million times this quantity is taken for the practical unit of electromotive force and called the *volt.*

The unit electrical current is that which flowing through one centimetre length of wire will create unit field at any point equidistant from all parts of the wire (as when the wire is bent to a curve of 1 cm. radius). One-tenth of this current is taken as the working unit and called the *ampère.*

The unit electrical resistance (one *ohm*) is that through which an electromotive force of one *volt* will force a current of one *ampère.*

The C. G. S. unit of work or energy is unit force acting through unit distance, that is one *dyne* acting through one centimetre. As this is too small to be generally convenient, ten million times this amount is taken as the working unit (called the *joule*). This is a little less than three-quarters of a foot-pound (exactly .7373). The unit *rate* of doing work is

one *joule* per second. This unit rate is called the *watt* and translating this into English measure, one *watt* equals $\frac{1}{746}$ *horse-power*.

Although the watt is often spoken of as an electrical unit, it belongs no more to electrical than to any other form of energy. It only remains to show the relation of the *watt* to the more strictly electrical units just mentioned. Recurring to our definition of the volt, let us suppose that the resistance of the circuit of which the moving wire is a part is such that unit electromotive force produces unit current in it. The stress between the field of the moving wire and the other unit field in which it moves is then one dyne at unit distance. In maintaining this for one second at the given rate of moving (1 cm. per second) the work done is, as above, one C. G. S. unit. At this rate if the E. M. F. were 1 *volt* and the current 1 *ampère*, the work would be one *joule* and the rate of doing work one *watt*. If either E. M. F. or current were changed, the work would be proportionally changed. So, the number of volts multiplied by the number of ampères is numerically equal to the *watts*, *i. e.*, we have obtained the dynamical equivalent of the two factors that make up electrical energy as ordinarily reckoned. So the output of any dynamo in watts is determined by the volt-ampères produced, and we see the reason of the ordinary statement that 746 *volt-ampères* make one horse power. This is always true whether the output is steady or variable, so long as we measure the product (volts and ampères) properly.

What few other electrical units appear in practical work will be referred to in their proper places.

It has been the purpose of this chapter, not so much to set forth the ordinary elements of electrical study, as to present these elements as viewed from the standpoint of energy. The author has purposely avoided the conception of electricity as a material something, in favor of the idea of stresses in the ether producing strains which are propagated through the ether, thus effecting the transmission of electrical energy. Hereafter we shall have to do with the extension of this transmission to practical magnitudes, and its utilization in the development of human industry.

CHAPTER II.

GENERAL CONDITIONS OF POWER TRANSMISSION.

THE growth of human industry depends on nothing more than upon the possession of cheap and convenient power. Labor is by far the largest factor in the cost of many manufactured articles, and in so far as motive power is cheap and easy of application it tends to displace the strength of human hands in all manufacturing processes and so to reduce the labor cost and to set free that labor for other and less purely machine-like purposes.

Therefore industrial operations have steadily gravitated toward regions where power is easily procured, often at the sacrifice of certain other advantages. This is in no wise better shown than by the growth of cities around easily available water powers even in regions where both raw material and finished product became subject to considerable cost of transportation. With the introduction of the steam engine came a corresponding tendency to gather factories about regions of cheap fuel. These localities, like those in which water power is plentiful, seldom coincide with centres of cheap material and transportation, so that it has generally been desirable to strike an average condition of maximum economy by transporting the necessary power, stored in the form of fuel, to some advantageous point.

Experience has shown however that, while the hauling of coal is a simple and comparatively cheap expedient, fuel utilized for running heat engines is in very many cases so much more expensive than hydraulic power as to be quite out of competition in cases where the latter can be transmitted with a reasonable degree of economy to places that are favorable for its utilization. And in general it is found that there is a wide field for the transmission of power obtained from a given source in competition with power from some other source utilized *in situ*.

The sources of energy on which we may draw for mechanical

power to be employed on the spot or transmitted elsewhere are very diversified, although few of them are to-day utilized in any considerable amount. Taking them in the order of their present importance we arrive at something like the following classification:

I. Fuel.
II. Water power (natural).
III. Wind.
IV. Solar radiation.
V. Tidal energy.
VI. Internal energy of the earth.

Of these only the first two play any important part in our industrial economy. The third is employed in a very small and spasmodic way, the fourth and fifth although enormous in amount are almost untouched, while the last is not at present used at all, owing to inherent difficulties.

I. The world's supply of fuel is almost too great for intelligible description. Aside from a widely distributed and steadily renewed supply of wood; the extent and capacity of available coalfields give promise that for a very long time to come fuel will be the chief source of energy. Coal is found in nearly every country and in most quite plentifully, while exploration both in old fields and in new, is constantly bringing to light fresh supplies. Many computations concerning the probable duration of the coal supply have been made, but they are generally unreliable owing to the great probability that only a very small proportion of the available coal is as yet known to mankind. Certain it is that there is unlikely to be a marked scarcity of fuel for several centuries to come, even at the present rate of increase in its consumption. Still it is altogether probable that it may become considerably dearer than at present within perhaps the coming century, owing to the increased difficulty of working the older mines and the comparative inaccessibility of new ones.

Besides coal we have petroleum and natural gas in unknown but surely very great quantities, since the distribution of both is far wider than has generally been supposed. At present the cost of these as fuels does not differ widely from that of coal, but appearances indicate that they are likely to be sooner exhausted.

Every improvement that is made in the generation of power by steam and its subsequent distribution helps to economize the fuel supply and stave off the already distant day when fuel shall be scarce. The work of the past half century has by direct improvement in steam practice nearly if not quite doubled the energy available per ton of fuel. Beyond this much has been done along collateral lines. Particularly, explosive vapor engines have been developed to a point at which they are for small powers decidedly more economical than steam engines. Gas engines of moderate size, 5 to 25 HP, are readily obtained of such excellence as to give a brake-horse-power hour on an expenditure of little, if any, more than 25 cu. ft. of ordinary gas, reducing the cost per HPH to below that of power from a steam engine of similar size. Engines using an explosive mixture of air and petroleum vapor are at least equally economical, in fact more so unless the comparison be made with very cheap gas.

These explosive engines have nearly double the net efficiency of steam engines as converters of thermal energy into mechanical power, and are capable of giving under favorable circumstances 1 HPH on the thermal equivalent of about 1 pound of coal.

II. Water power derived from streams is not distributed with the same lavish impartiality as fuel, but nevertheless exists in many regions in sufficient amount to be of the greatest importance in industrial operations. Available streams exist around almost every mountain range and are capable of furnishing an amount of power that is seldom realized. In the United States the total horse power of the improved water power is approximately 1,500,000. New England is especially rich in this respect, as is, too, the entire region bordering on the Appalachian range. The Rocky Mountains are less favored, the available water being rather small in amount on account of the smaller rainfall.

The Pacific slope is rather better off and the high price of coal operates to hasten the development of every practicable power. All over the country are scattered small water powers, and one of the interesting results of the growth of electrical power transmission has been to bring to light half forgotten falls even in familiar streams. Abroad, Switzerland is rich in powers of

moderate size, as is the entire Alpine region, while a few years of experience in electrical transmission will probably cause the discovery or utilization of many water powers that have hardly been considered, even in highly developed countries. Of the world's total water power supply we know hardly more than of its coal supply, but it is quite certain, now that transmission of power over very considerable distances is practicable, that the employment of the one will every year lessen the relative inroads upon the other. And this is in spite of the fact that water is by no means always cheaper than steam as a motive agent.

III. Wind as a prime mover has been employed on a rather small scale from the very earliest times. Were it not for the extreme irregularity of the power supplied by it in most places, the windmill would be to-day a very important factor in the problem of cheap power. Unhappily winds in the same place vary most erratically from the merest breeze to a hurricane sweeping along at the rate of 50 to 75 miles an hour. As all strengths of wind within very wide limits must be utilized by the same apparatus running at all sorts of speeds, it is no easy matter to employ it for most sorts of work. It seems specially unfitted for electrical work, and yet several small private plants have obtained good results from windmills used in connection with storage batteries.

In ordinary winds the great size of the wheel necessary for a moderate power militates against any very extensive use. For example, with a good breeze of 10 miles per hour a wheel about twenty-five feet in diameter is needed to produce steadily a single effective horse power, and the rate of rotation, about 30 revolutions per minute, is so low as to be inconvenient for many purposes. Hence windmills are generally used for very small work which can be done at variable speed, such as pumping, grinding and the like, for which they are unexcelled in cheapness and convenience. For large work we can hardly count much on wind power, in spite of ingenious speculations to the contrary, and as a source of power for general distribution it is out of the question, for such as it is we have it already distributed. It must rather be regarded as a local competitor of distributed power, and even so only in a small and limited field.

IV. Aside from being in a general way the ultimate source

of nearly all terrestrial energy, the sun steadily furnishes an amount of radiant energy which if converted into mechanical power would more than supply all possible human needs. Its full value is the equivalent of no less than ten thousand horse power per acre of surface exposed to the perpendicular rays of the sun.

This prodigious amount is reduced by perhaps one-third through atmospheric absorption before it reaches the sea level, and in cloudy weather by a very much larger amount. Nevertheless with clear sunlight the amount of energy practically available, after making all allowances for increased absorption when the sun is low, and for the hours of darkness in any given place, is very great. If we suppose the radiant energy to be received on concave mirrors kept turned toward the sun and arranged so as to utilize the heat in the boiler of a steam or vapor engine, the average result after making all allowances for losses would be one mechanical horse power for each 100 square feet of mirror-aperture, available about ten hours per day. This efficiency has been substantially realized in practice, for such a solar engine constructed by M. Mouchot actually gave nearly a horse power with a mirror surface of about 100 square feet.

Such an engine would not be available at all times owing to clouds, but might very well prove useful in some climates for irrigation work. During the dry season it could be operated almost every day, and with the advantage over windmills of giving quite steady power and at any convenient speed. Although not of general applicability, such apparatus might be very valuable in portions of the desert country west of the Rocky Mountains, in Mexico, western South America, northern Africa and elsewhere. So, if mankind ever is in dire need of power, the sun stands ready to furnish it.

V. Of tidal energy but little use has yet been made. Here and there both here and abroad are small tidemills, feebly suggesting the enormous store of tidal power as yet unutilized. The intermittent character of tidal currents and the small extent of the rise and fall generally available make the practical part of the problem somewhat difficult. The easiest way of harnessing the tides is to let the rising water store itself in artificial reservoirs or natural ones artificially improved and then during

the ebb to use it with water-wheels. But usually the head is so small that for any considerable power stored the area of reservoir must be very large and the wheels must be of great size in order to make the stored water do its work before the rising tide checks further operations. The average tide is seldom more than 10 to 12 feet along our coast, and of this hardly more than half could be utilized to give even a few hours of daily service. At 6 feet available head about 100 cubic feet of water must be stored for each horse-power-minute, even with the best modern turbines. Hence for say 1,000 HP available for 5 hours there must be impounded 30,000,000 cubic feet of water, making a pond 6 feet deep and almost 120 acres in extent.

Tidal operations are therefore likely to be restricted to a few favored localities where through natural configuration of the ground natural reservoirs can be found and where the rise of the tide is several times the figure named. In rare cases by the use of more than one reservoir and outlet work may be made nearly or quite continuous. Still with all these difficulties the possibilities of tidal power are enormous in special cases. Take for example the Bay of Fundy with its 40 feet of normal tidal rise. If half this head can be used in practice 30 cubic feet will be required per horse-power-minute, and a single square mile of reservoir capacity gained by damming an estuary or cutting into a favorable location on shore will yield 62,000 horse power ten hours per day in two five-hour intervals. Generally speaking, economic conditions are not favorable for such an employment of the tides, but in some localities a peculiarly fortunate contour of the shore coupled with high local cost of fuel may render it easy and profitable to press the tides into service. The author has had occasion to investigate a few cases of this kind in which the commercial outlook was good.

VI. Of the earth's internal heat energy there is little to be said. It is quite unused and except in a very few cases could not be employed at all, much less to any advantage. Immense as is its aggregate amount it is, save at isolated points, so far separated from the earth's surface as to be very difficult to get at. Hot springs, very deep artesian wells and some volcanic regions furnish the only feasible sources of terrestrial heat energy, so that the whole matter is only of theoretical interest.

We see then that at present only two sources of energy, viz., fuel and water power, are worthy of serious consideration in connection with the general problem of the transmission and distribution of power. The other sources enumerated are either very irregular, uncertain in amount, or so difficult of utilization as to remove them at once from the sphere of practical work.

Granted then that fuel and water power are and are likely long to remain the dominant sources of energy, let us look more closely into their possibilities. From each energy can be readily transmitted and distributed by any suitable means; each in fact can be transferred bodily to a distant scene of action without any transformation from its own proper form. In fact for certain purposes and under certain conditions such is the very best method. Fuel for ordinary heating and water for such uses as hydraulic mining can be taken as cases in point. In a more general way both fuel and water for the development of mechanical power may often profitably be transferred from place to place.

The conditions of economy in the transmission of fuel as such are comparatively easy to examine and define. Coal may be produced at the mine for a certain quite definite cost per ton. It can be transported over railroads and waterways for an easily ascertainable price. Such a transmission may be said to have a definite efficiency, as for example 90 per cent. when the total transportation charges against a ton of coal amount to 10 per cent. of its final value. From this standpoint it is quite possible to transmit power at this very high efficiency even to the distance of hundreds of miles. If the final object be the distribution of power on a large scale, as from a great central station, this transmission by transportation of fuel is often at once the most reliable and the cheapest method.

Transformation of the fuel energy at its source into some other form for the purpose of transmission is generally only justifiable, first, when by so doing fuel not available for transportation at a high efficiency can be rendered valuable by transformation of its energy, or second, when it is to be utilized at some distant point in a manner which compels a loss of efficiency greater than that encountered in transmission. As an example of the first condition fully one-third of the coal as ordinarily

mined is unfitted, through its finely divided condition or poor quality, for transportation over considerable distances. Its commercial value is so small per ton that it could not be carried far without incurring charges for carriage amounting to a large part of its value. Hence every coal mine accumulates a mountainous culm pile that is not only at present valueless but cumbers the ground. This waste product could sometimes be very profitably employed in generating power which could be transmitted at a relatively very high efficiency and sold at a good price.

A specimen of the second kind may be found in the somewhat rare case of power which must be used in small units scattered over a considerable territory, so that they could be replaced with a great gain in efficiency by a single large generating station. Such a state of affairs might be found in certain mining regions where coal and iron mines are interspersed. This must not be confounded with the very ordinary case of distributing energy from a central station to various scattered points, for we are here considering only the original source of the fuel.

When an extensive distribution of energy from a power station is contemplated, electrical or similar transmission of power to that station is generally economical only on the condition above expressed, of using fuel otherwise valueless, since the facilities for transportation to points at which power distribution on a large scale would be profitable, are generally good and fairly cheap. All this applies to piping gas or petroleum as well as to hauling coal. It has even been proposed to pipe coal dust by pneumatic power for fuel purposes.

Water power is by no means always cheaper than fuel, but as a general rule it is, and by such an amount that it can be transformed into electrical energy and transmitted to at least a moderate distance without losing its economic advantage. It therefore is often the cheapest source from which to derive power for general distribution on a large scale.

It is very difficult to give a clear idea of the relative cost of steam and water power, for while the one can be predicted for any given place with fair accuracy, the other is subject to immense variations. Once established, a water power plant can be operated very cheaply, but the cost of developing the

water power may be almost anything, and each case must be figured by itself. It is easy to obtain estimates of the cost of developing a given stream and to form a close estimate of both the interest charges to be incurred and the additional expense of repairs and of operation. The cost of steam power for the same conditions can be accurately estimated. The details of such estimates we will discuss later. In general one can only safely say that the costs of steam and water power overlap, as it were, so that while the more easily developed water powers are cheaper sources of energy than fuel at any ordinary price, there are many cases in which the great cost of development of difficult water powers prohibits competition with steam except where fuel is very dear. Much depends on the topography of the country, the amount and reliability of the available head of water, the price at which water rights can be obtained and various other local conditions. To utilize the normal minimum power of a stream is generally comparatively easy, while so to take account of high water as to obtain nearly the full continuous working power of the stream often means great added expense for storage capacity and works to control and regulate the flow.

In addition we have to consider two distinct phases of the comparative cost—first, the cost of steam and water as prime movers for a source of power to be distributed, and second, the relation between these costs and that of steam power at the points where the distribution takes place.

Given a proper source of energy, there is vast variety in the character of the work of transmission and distribution that is to be undertaken. In the first place the point of utilization may be distant anywhere from a few hundred feet to many miles, and at that point the object may be the delivery of mechanical power in a single unit, in one or several groups of allied units, in one or several widely scattered groups, or finally for transformation into some other form of energy in the most direct way possible.

There is no single method of power transmission which meets in the best possible manner all these widely varying conditions. Although electrical transmission is the most general solution of the difficult problem in hand, there are cases in which other methods are preferable and should be adopted.

Those besides electric transmission which have come into considerable use are the following:

I. Wire Rope Transmission.
II. Hydraulic Transmission.
III. Compressed Air Transmission.
IV. Gas Transmission.

It will be well to look into the distinguishing characteristics of these and their relation to electrical transmission with the purpose of finding the advantages and limitations of each, so that the proper economic sphere of each may be determined, before taking up the electrical work which forms the main subject of this volume. Each method will be found to have its own legitimate place.

I. The transmission of power by wire ropes is merely a very useful extension of the ordinary process of belting. Belts are made of material which will not stand exposure to the weather, and which being of low tensile strength is heavy and bulky in proportion to the power transmitted. The advantage of wire rope over belting lies in its high tensile strength and freedom from deterioration when used out of doors. To gain the fullest benefit from these properties it is necessary to use light ropes driven at high speed.

It should be borne in mind that the power transmitted by anything of the nature of belting depends directly on the speed and the amount of pull exercised. If the force of the pull is 100 pounds weight and the speed of belt or rope is 4,000 feet per minute the amount of power transmitted is 400,000 foot-pounds per minute or (since 1 horse power is 33,000 foot-pounds per minute) about 12 HP. The greater the speed the more power transmitted with the same pull, or the less the pull for the same power. Wire rope can be safely run at a considerably higher speed than belting and is much stronger in proportion to its size and weight. It does not often replace belting for ordinary work for the reason that owing to its small size it does not grip ordinary pulleys anywhere nearly in proportion to its strength. Hence to best take advantage of its ability to transmit large powers the rope speed must be high and the pulleys unusually large in diameter to give sufficient surface of contact. Such large wheels are inconvenient in most situations, and as the alternative is a

number of ropes which are troublesome to care for, rope driving save for outdoor work is rather uncommon.

A typical rope transmission is shown diagrammatically in Fig. 10. Here *A* and *B* are two wheels, usually of cast iron, generally from 5 to 15 feet in diameter and with deeply grooved rims. They are connected by a wire rope perhaps from ½ inch to 1½ inch in diameter, which serves to transmit the power as the

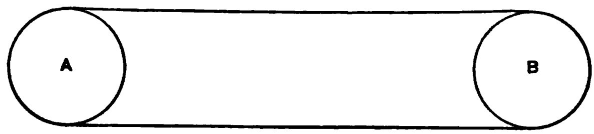


FIG. 10.

wheels revolve. The rope speed is usually from 3,000 to 5,000 feet per minute, sometimes as high as 6,000. The distance between the centres of *A* and *B* may be anything required by the conditions up to four or even five hundred feet. Greater distances are seldom attempted in a single span, as if the rope is not to be overstrained by its own weight it must be allowed to sag considerably, compelling the pulleys to be raised to keep it clear of the ground, and subjecting it to danger from swaying seriously by reason of wind pressure or other accidental causes.

The rope employed is of special character. The material is the best charcoal iron or low steel, and the strands are usually.

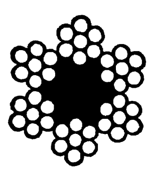


FIG. 11.

laid around a hemp core to give added flexibility. The rope generally employed in this country is of six strands with seven wires per strand, and is shown in cross section in Fig. 11. Even with the hemp core there is still in an iron rope sufficient resistance to bending to make the use of pulleys of large diameter necessary. Sometimes each separate strand is made with a hemp core or is composed of nineteen small wires

instead of seven larger ones, to increase the flexibility and to make it possible to use smaller sheaves and drums, as in hoisting machinery.

Steel rope is slightly more costly than iron, but gives greater durability. The wheels on which these ropes run are furnished with a deep groove around the circumference, provided with a relatively soft packing at the bottom on which the rope rests, and which serves to increase the grip of the rope and to decrease the wear upon it. Fig. 12 shows a section

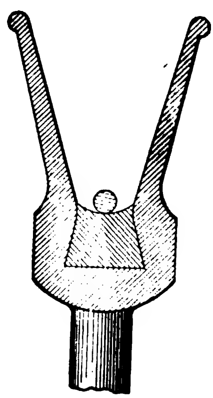


FIG. 12.

of the rim of such a wheel. The bushing at the bottom of the groove, upon which the rope directly bears, has been made of various materials, but at present leather and specially prepared rubber are in most general use. The small pieces of which the bushing is composed are cut to shape and driven into the dovetailed recess at the bottom of the groove. The bushings have to be replaced at frequent intervals, and the cables themselves have an average life of not much over a year.

When a straightaway transmission of a few hundred feet is necessary, when the power concerned is not great and the size of the pulleys is not a serious inconvenience, this transmission by wire rope is both very cheap and enormously efficient. No other known method can compete with it within these somewhat narrow limitations. For a span of ordinary length and the usual rope speeds the efficiency has been shown by experiment to be between 96 and 97 per cent. At a dis-

tance of four to five hundred feet the weight and sag of the rope becomes a very serious inconvenience and the arrangement has to be modified. Perhaps the most obvious plan is to introduce a sheave to support the slack of the cable, as shown in Fig. 13.

On longer spans several sheaves become necessary and both the slack and the tight portions of the cable need such support.

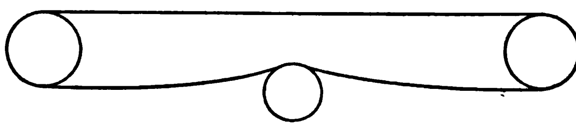


FIG. 13.

In cable railway work, the most familiar instance of power transmission by wire ropes, numerous sheaves have to be employed to keep the cable in its working position in the somewhat contracted conduit. These reduce the efficiency of the system considerably, so that the power taken to run the cable light is often greater than the net power transmitted. In aerial cable lines multiple sheaves are seldom used, and the more usual procedure is to subdivide the transmission into several independent spans, thus lessening swaying and sagging as well as the length of rope that must be discarded in case of a serious break. This device is shown in Fig. 14. It employs intermediate pulley stations at which are installed double

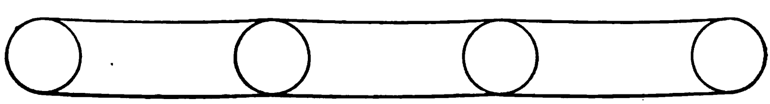


FIG. 14.

grooved pulleys to accommodate the separate cables that form the individual spans. Such a pulley is shown in section in Fig. 15. The spans may be three or four hundred feet long; as soon as the length gets troublesome another pulley station is employed. There is necessarily a certain small loss of energy at each such station. This is approximately proportional to the number of times the rope passes over a pulley. From the best experimental data available the

efficiency of a rope transmission extended by separate spans is nearly as follows:

Number of spans, . . .	1	2	3	4	5	6	7	8	9	10
Per cent. efficiency, . .	.96	.94	.93	.91	.89	.87	.86	.85	.84	.82

These figures are taken to the nearest per cent. and are for full load only. At half load the loss in each case would be

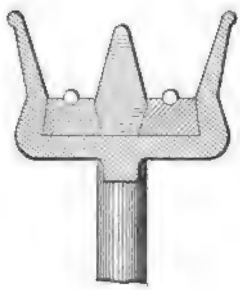


FIG. 15.

doubled. For instance a 10-span transmission at half load would give but 64 per cent. efficiency. The pulley stations consist of the double-grooved wheel before mentioned mounted on a substantial and rather high pedestal or frame-work.

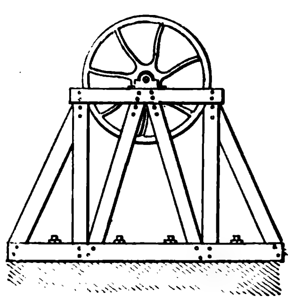


FIG. 16.

In this country a timber frame is generally used; abroad a masonry pier is more common. A convenient form of frame-work is shown in Fig. 16. An idea of its dimensions may be gained from the fact that the wheel is likely to be 6 to 10 feet in diameter.

It is interesting to note that the efficiency just given for a 10-span transmission at full load is quite nearly the same as would be obtained from an electrical power transmission at moderate voltage over the same distance, assuming a unit of say 50 HP or upward. The first cost of the latter would be considerably higher than that of the rope transmission, but the repairs would almost certainly be less than the replacements of cable, bringing the cost per HP at full load to about the same figure by the two methods.

From actual tests of electrical apparatus we have the following efficiency for a transmission of 50 HP 5,000 feet,

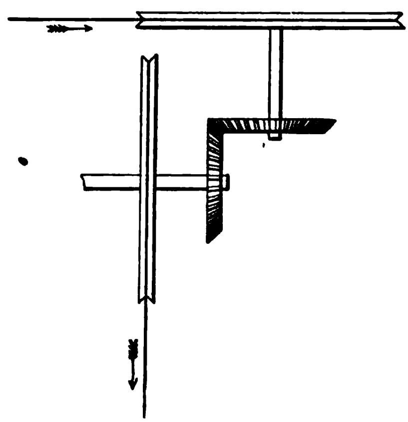


FIG. 17.

assuming 2,000 volts and 2 per cent. line loss, which would require a wire less than one-fourth of an inch in diameter. Efficiency at full load 81 per cent., at half load 72. Except at full load the electrical transmission has a very material advantage. This advantage would be greatly increased if the transmission were in anything but a straight line. An electric line can be carried around any number of corners without loss of efficiency, while a rope transmission cannot. If it becomes needful to change the direction of a rope drive it is done at a station provided with a pair of rope wheels connected by bevel gears set at any required angle. Fig. 17 shows such a station in diagram. The loss of energy in such a pair of bevel gears amounts to from 7 to 10 per

cent., more often the latter. The bevel gears may be avoided by a sheave revolving in a horizontal plane and carrying the turn in the cable, but while this arrangement is tolerably efficient it greatly decreases the life of the rope.

From what has been said it will be seen that while cable transmission is for short distances in a straight line both cheap and very efficient, at 4,000 to 5,000 feet it is equalled and surpassed in efficiency by electric transmission, with lesser maintenance although greater first cost. The steel rope for a 50 HP transmission of 5,000 feet would cost about $300, and replacement brings a considerable charge against each HP delivered. If the transmission is not straight away or if branches have to be taken off *en route* the efficiency of the system is considerably reduced by gear stations, while even aside from these the efficiency is high only at or near full load. But the general simplicity and cheapness of cable transmission has made it a favorite method, and there have been many such installations, some of them of a quite elaborate character. Most of them are small, since the amount of power that can be transmitted by a single rope is limited to 250 or 300 HP. Ropes suited to a larger power are too heavy and inflexible; 1¼ inch is about the greatest practicable diameter of cable, and even this requires pulleys between 15 and 20 feet in diameter for its proper operation.

One of the oldest and most considerable rope transmissions is that at Schaffhausen, where power derived from the falls of the Rhine is utilized for distribution to a number of factories in the vicinity. As a typical case it is worth more than a passing mention.

The turbine house contains three vertical shaft turbines aggregating 760 HP, working under about 15 feet head and geared to a common horizontal shaft. Any turbine can be put out of gear at will. The main shaft makes 80 revolutions per minute and carries loose upon it the main driving pulleys, each of which is 14′ 9″ in diameter. These are connected by bevel gears which mesh into a pair carried on studs driven by the shaft. Thus if there is any difference in the tension of the two main cables the pulley carrying the lesser load is accelerated and the rope tensions are brought to equality. From the turbine house the main line crosses to the left bank

of the Rhine and is turned at right angles by a bevel gear station. Then follow three spans along the river bank and then a second oblique gear station. The driven span of this terminates the main transmission, of which the total length is about 2,000 feet. From each pulley station power is taken off laterally by shafts or ropes for driving various factories, and beyond the main cables are smaller ones to continue the distribution. In all more than a score of customers are served and the nominal HP supplied is over 600. The charge for power is from $24 to $30 per HP per year. With various renewals, extensions and modifications the system has been steadily at work for more than a quarter of a century. The principal troubles have been loss of efficiency in bad weather and a tendency to oscillations of the rope and irregularity of speed at full load. One spinning mill abandoned the transmitted power on account of the severe changes of speed. Financially the Schaffhausen plant has been a success, from the Continental standard of profit at least, but it is even now the only similar plant where a general scheme of distribution is thoroughly worked out. It is found very difficult to measure equitably the power delivered to customers.

Let us now inquire into the efficiency of this transmission. There are on the average at least five spans of cable between the turbines and the vicinity of each factory. At full load this would under the most favorable circumstances give an efficiency of about .90. This load certainly exists only in the main driving spans. The power delivered is in most cases transferred to the working main shafts by subsidiary rope drives or by shafting. If the average working efficiency of this is above .90 under normal conditions of load our experience with similar devices elsewhere counts for little. Then there are two bevel gear stations to be considered, each of which can hardly exceed .92 in efficiency. The total probable efficiency from the main shaft in the turbine house to the main shafts of the factories at substantially full load is at best only $.90 \times .90 \times .92 \times .92 = .68$, and at ¾ load, which represents a much more likely state of affairs, about .52. Even the higher figure compares sadly enough with that just given for a single small electrical transmission over a greater distance,—.81 at full load. With the most ordinary electrical transmission

over the same distance the net efficiency from generator shaft to motor shaft would be at least .75 at full load. It is worthy of note that in an extension of the Schaffhausen works made within the last few years, the cable system was abandoned and electrical apparatus installed for the additional plant.

Although for a single straight transmission the cable system is up to nearly a mile more efficient than any other yet devised, it is sufficiently evident that when distribution is to be done involving changes of direction and many small rope drives or shafts, the advantage in efficiency very rapidly disappears, and at anything but full load the system is anything but efficient. Under all circumstances the need of replacing the cables every year or so causes a high rate of maintenance. The following table, giving the sizes of iron wire cables and pulleys necessary for transmitting various amounts of power, will help to give a clearer idea of the conditions of cable transmission and aid in defining its limited but useful sphere. Speed is given in revolutions per minute and pulley diameter is the smallest permissible. These figures are, as will readily be seen, for rope

Diam. of Rope.	Speed.	Diam. of Pulley.	HP.
½″	150	6′	25
9/16″	140	7′	35
⅝″	140	8′	45
11/16″	100	10′	85
¾″	80	12′	100
1″	80	14′	140
1⅛″	80	14′	150

speeds of not far from 3,000 feet per minute. This can frequently be safely raised to 5,000 with somewhat larger pulleys than those given and increased revolutions, while for steady loads the tension can be slightly augmented without danger. So while the figures given are those suitable for ordinary running with a good margin of capacity, the HP given can be nearly doubled when all conditions are favorable.

II. Noting then that cable transmission does excellent work in its proper place, but is unsuited for the distribution of power or for transmissions more than 3,000 to 4,000 feet in length, we

may pass to the hydraulic method of transmitting and distributing power. This in its crude form of small water motors attached to ordinary city mains is very familiar, but nothing more extensive has been attempted in this country. Abroad there are a number of hydraulic power plants specially intended for the distribution of power for general use, and the method is one which has been fairly successful. There are two distinct types of hydraulic plant, one utilizing such pressure as is available naturally or by pumping to reservoirs, the other employing very high artificial pressures, up to 750 pounds per square inch, and used only for special purposes.

There are somewhat extensive works of the former kind at Zurich, Geneva, and Genoa, the effective head of water being in each case not far from 500 feet. In each case the power business has been an outgrowth of the municipal water supply system. At Zurich and Geneva elevated reservoirs are supplied by pumping stations driven by water power. At Genoa the head is a natural one, 20 miles from the city, and much of the fall is utilized 18 miles from Genoa in driving the fine constant current electric plant described elsewhere in this volume.

At Zurich there is in addition to the ordinary low pressure water system a special high service reservoir supplying power to a large electric station and to small consumers. Water is pumped 6,000 feet into this reservoir through an 18-inch main and the total power service from both systems is something like 500 HP, reckoned on a ten-hour basis. The price charged is from $37 to $80 per HP per year.

The Geneva plant is on a much larger scale, the total turbine capacity being about 4,500 HP. Here, as at Zurich, there are two sets of mains, one at nearly 200 feet head, the other at about 450. Both supply water for both power and general purposes. The high pressure service reservoir is about 2½ miles from the city and the working pressure is supplied indifferently from this or from the pumps direct. There is an electric light plant with 600 HP in turbines driven by the pressure water and a large number of smaller consumers. Water is supplied to the electric light company for as low as $15 per HP per year.

Both these installations are extensions of the city water service, and have done excellent work. Operated in this way

the economic conditions are somewhat different from those to be found in a hydraulic plant established by private enterprise for power only. An inquiry into the efficiency of such a system may be fairly based on the facts given. At Zurich, for example, the efficiency from turbine shaft to reservoir cannot well exceed .75. The distributing mains must involve a loss of not less than 10 per cent., while the motors cannot be counted on for an efficiency of over .75. The total efficiency from turbine shaft to motor shaft is then about $.75 \times .75 \times .90 = 50.6$ per cent. The character of the motors has an impor-

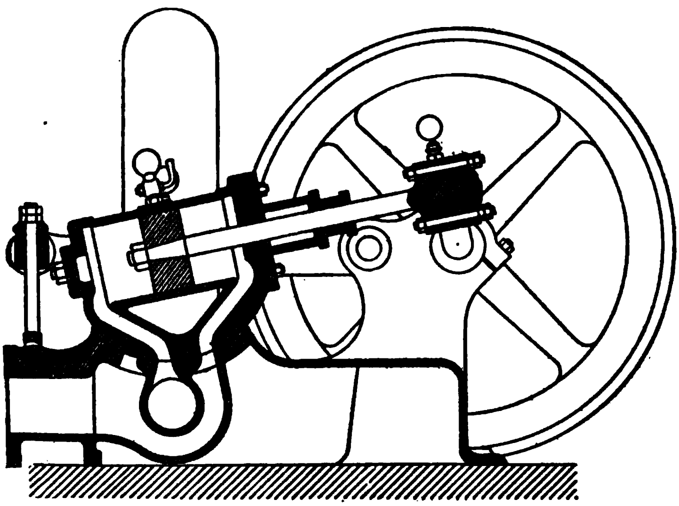


FIG. 18.

tant influence on the economy of the system, particularly at low loads. The motors most used particularly for small powers are oscillating water engines of the type shown in Fig. 18. The form shown is made by Schmid of Zurich. It possesses in common with all others of similar construction the undesirable property of taking a uniform amount of water at uniform speed, quite irrespective of load. The mechanical efficiency falls off like that of a steam engine, friction being nearly constant. Better average results are secured with impulse turbines (see Chapter VII.) of which the efficiency varies but little as the load falls off, or for high rotative speeds with impulse wheels like the

Pelton, shown in Fig 19, as adapted for motors of moderate power. At half load, *i. e.*, half flow, the losses in distributing mains would be reduced to about one-third, while the efficiency of the engine motors would certainly not be lowered by less than 5 per cent. The total half load efficiency would then be $.75 \times .97 \times .70 = 50.9$ per cent., actually a trifle higher than at full load. This rather remarkable property is shared by electric transmissions wherein the line loss is fairly large, and is occasionally of value.

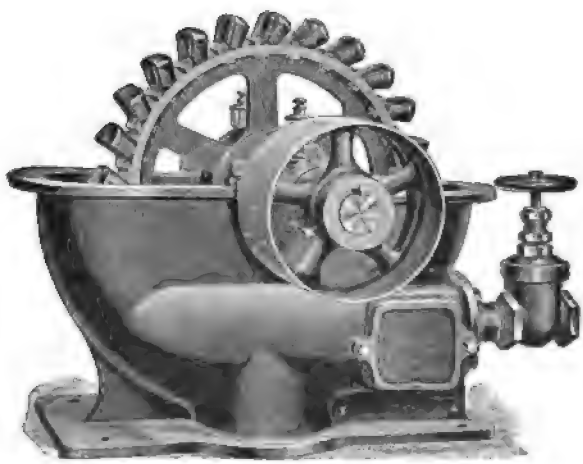


FIG. 19.

The second type of hydraulic distribution of power is that at very high pressures and employing a purely artificial head. The pressures involved are usually 700 to 800 pounds per square inch, and a small amount of storage capacity is gained by employing what are known as hydraulic accumulators, fed by the pressure pumps. These accumulators are merely long vertical cylinders adapted to withstand the working pressure, which is kept up by a closely fitting and enormously heavy piston. The distribution of power is by iron pipes leading to the various water motors. This high pressure water system is a device almost peculiar to England, and has been slow in making headway elsewhere. Its peculiar advantage is in connection with an exceedingly intermittent load, such as is

obtained from cranes, hoists, and the like. This is for the reason that with a low average output a comparatively small engine and pump working continuously at nearly uniform load can keep the accumulators charged, while the rate of output of the accumulators is enormous in case of a brief demand for very great power.

Power plants on this hydraulic accumulator system are in operation in the cities of London, Liverpool, Hull, and Birmingham, England, and at Marseilles, France. Others are under construction at Manchester, England, and Antwerp, these last being worked out in connection with electric substations—a singular vagary, highly original and uniquely inefficient. The London plant is the most important of those mentioned, consisting of three pumping and accumulator stations and about 60 miles of mains. The total number of motors operated was in 1892 about 1,700. The charges are by meter, and are based on intermittent work, being quite prohibitive for continuous service—from $200 to $500 per effective HP per year of 3,000 hours. The largest accumulators have pistons 20 inches in diameter and 23 feet stroke, giving a storage capacity of only 24 horse-power-hours each. While very convenient for the supply of power for intermittent service only, this system, like hydraulic supply at low pressure, is rather inefficient, the more so as it has been found advisable to employ hydraulic motors of the piston type, although special Pelton motors have been used in some cases.

Any hydraulic system suffers severely from the inefficiency of pump and motors and from loss of head in the pipes. The amount of power that can be transmitted in the mains is quite limited, since the permissible velocity is not large. About 3 feet per second is customary—more than this involves excessive friction and danger from hydraulic shock. At this speed a pipe about 2 feet in diameter is necessary to transmit 500 HP under 500 feet head.* The power delivered increases directly with the head, but as the pressure increases the largest practicable size of pipe decreases, and on the high pressure systems nothing larger than 12 inches has been attempted, and even this requires the use of solid drawn steel.

* Cost per mile laid in average unpaved ground about $15,000.

Whatever the size of pipe the loss in head is quite nearly inversely as the diameter and directly as the square of the velocity. Even for high pressure systems this loss is by no means negligible, since the pipes used are rather small.

The following table gives the loss of head in feet per 100 feet of pipe and at a uniform velocity of 3 feet per second. This applies to pipe in good average condition. When the pipe is new and quite clean the losses may be slightly less. If the pipe is old and incrusted the above losses may be nearly doubled. Bends and branches still further reduce the working pressure.

Diameter	1"	2"	3"	4'	5"	6"	7"	8"	10"	12"
Loss of Head	4.89	2.44	1.62	1.22	.98	.81	.70	.61	.49	.41
Diameter	14"	16"	18"	20"	22"	24"	26"	28"	40"	36"
Loss of Head	.35	.32	.27	.25	.22	.20	[illegible]	.17	.16	.13

We may now look into the efficiency of these high pressure hydraulic systems. Of the mechanical horse-power applied to the pump we cannot hope reasonably to get more than .75 per cent. as energy stored in the accumulators. Tests on the Marseilles plant have shown 70 to 80 per cent. efficiency between the indicated steam power and the accumulators, the former figure at the speeds corresponding to full working capacity. As the pumps were direct acting the difference between brake and indicated HP was presumably very small. The motors can be counted on for about .75 efficiency, and the losses of head in the pipes for any ordinary distribution cannot safely be taken at less than 5 per cent. Hence the full load efficiency is about $.75 \times .75 \times .95 = .53$. The efficiency at full load is thus not far from that of the low pressure system, but at half load it suffers from the use of piston motors, generally necessary on account of the too high speed of rotary motors at high pressure. At even 500 pounds per square inch pressure the normal speed of a Pelton wheel of say 20 HP would be over 4,000 r. p. m., and could not be greatly reduced without seriously cutting down the efficiency. At half load the piston motors could not be relied on for over .65 efficiency, reducing the total efficiency,

even allowing for greatly lessened pipe loss, to about 45 per cent.

The strongest point of hydraulic transmission is its ready adaptability in connection with water supply systems for general purposes. Skillfully installed, as for instance at Geneva, it furnishes convenient, reliable, and fairly cheap motive power. As a distinct power enterprise the high first cost is against it, and the efficiency is never really good. All this applies with equal force to the special high pressure systems, which suffer from inability to cope with continuous work, thus seriously limiting the possible market. Even for intermittent service the charges are enormously high.

The methods of power transmission already mentioned are then somewhat limited in their usefulness by rather well defined conditions, which make their employment advisable in some cases and definitely inadvisable in general.

Transmission by wire ropes is very weak in the matter of distribution to numerous small units, and hydraulic transmission, while escaping this difficulty, is, save in exceptional cases, both inefficient and costly.

III. We may now pass to the pneumatic method of transmitting power, which is far more general in its convenient applicability than either of the others, and which is the only system other than electric which has been extensively applied in practice to the distribution of power in small units, although only short distances have been involved in any of the plants hitherto operated, and the possible performance at long distances is more a subject of speculation than of reasonable certainty. Transmission of power by compressed air involves essentially three elements: An air compressor delivering the air under a tension of from 50 to 100 or more pounds per square inch into a pipe system, which conveys the compressed air to the various motors. These motors are substantially steam engines in mechanical arrangements, and indeed almost any steam engine can be readily adapted for use with compressed air. The compressor itself is not unlike an ordinary steam pump in general arrangement. Its appearance in the smaller sizes is well shown in diagram in Fig. 20. The system was originally introduced about fifty years ago for mining purposes, and owed its early notoriety to its use in working

the drills in the construction of the Hoosac, Mont Cenis and St. Gothard tunnels. Since then it has come to be used on a very extensive scale for drilling operations and more recently has been applied for the distribution of power for general purposes, particularly in Paris, where the only really extensive system of this kind is in operation. Its best field has been and still is in mining operations where the escaping air is a welcome addition to the means of ventilation and where, as a rule, the distances are not great.

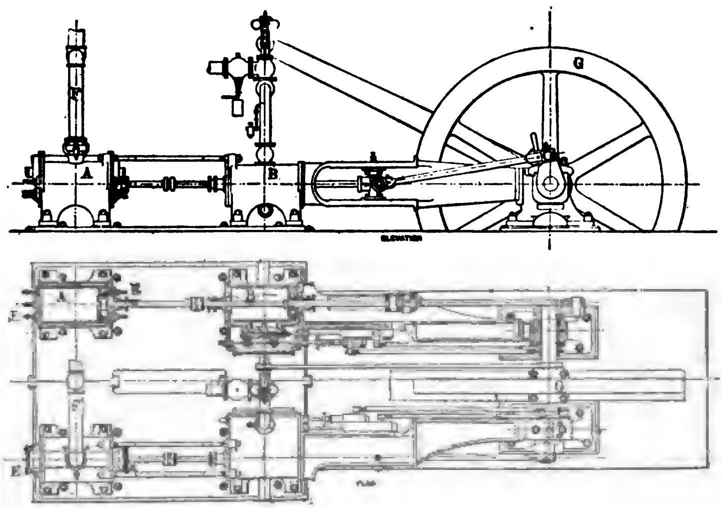


FIG. 20.

Transmission of power by piping compressed air has even for general distribution certain very well marked advantages. The subdivision of the power can be carried on to almost any extent and the motors are fairly efficient, simple and relatively cheap. In addition, the power furnished to consumers can very easily be metered. The loss of energy can be kept within moderate limits and the mains themselves are not liable to serious breakdowns, although losses from leakage are frequent and may be large. Finally, the system is exceptionally safe. On the other hand, the efficiency of the system, reckoned to the motor pulleys, is exceedingly low. The mains for a transmission of any con-

siderable length are very costly, and the compressed air has no considerable use aside from motive power, instead of being applicable, like electric or even hydraulic transmission of power, to divers profitable employments quite apart from the furnishing of mechanical energy. To obtain a clearer idea of the nature of these advantages and disadvantages, let us follow the process of pneumatic transmission from the compressor to the motor, looking into each stage of the operation with reference to its efficiency and economic value.

The compressor is the starting point of the operation. Fig. 20 shows in section a typical direct acting steam compressor, one of the best of its class. It consists essentially of the air cylinder *A* and a steam cylinder *B*, arranged in line and having a common piston rod. The steam end of the machine is simply an ordinary engine fitted with an excellent high speed valve gear worked by two eccentrics on the crank shaft of the fly wheels *G*, which serve merely to steady the action of the mechanism. The air cylinder *A* is provided with a simple piston driven by an extension of the steam piston rod.

At each end of the air cylinder are automatic poppet valves *E E*, which serve to admit the air and to retain it during the process of compression. *F* is the discharge pipe for the compressed air leaving the cylinder. In the compressor shown there are two steam and two air cylinders connected with the cranks 90° apart, thus giving steady rotation in spite of the character of the work. In some machines the pistons and piston rods are hollow and provided with means for maintaining water circulation through them, to assist in cooling the air. Round the air cylinder is a water jacket shown in the cut just outside the cylinder wall. The purpose of this is to keep the air, so far as possible, cool during compression and thus to avoid putting upon the machine the work of compressing air at a pressure enhanced by the heat that always is produced when air is compressed. And just here is the first weak point of the compressed air system. However efficient is the mechanism of the compressor, all heat given to the air during compression represents a loss of energy, since the air loses this heat energy before it reaches the point of consumption. The higher the final pressure which is to be reached the

more useless heating of the air and the lower efficiency. Hence the water jacket, which, by abstracting part of the heat of compression, aids in averting needless work on the air during compression. Even the most thorough jacketing leaves much to be desired, generally leaving the air discharged at from 200° to 300° F., more often the latter. A cold water spray is often used in the compressing cylinder. This is somewhat more thorough than the jacket, but is still rather ineffective. Both serve only to mitigate the evil, since they cool the air by absorbing energy from it and at best cool it very imperfectly. A careful series of investigations by Riedler, perhaps the best authority on the subject, gives for the efficiency of the process of compression from .49 to .72. These figures, derived from seven compressors of various sizes and types, include only those losses which are due to heat, valve leakage, clearance and the like, taking no account of frictional losses in the mechanism. These are ordinarily about the same as in a steam engine, say 10 per cent., so that the total efficiency of a simple compressor may be taken as .44 to .65, the latter only in large machines under very favorable conditions. The most considerable recent improvement in compressors is the division of the compression into two or more stages, as the expansion is divided in compound and triple expansion engines. This limits the range of heating that can take place in any given cylinder and greatly facilitates effective cooling of the air. Riedler has obtained from two-stage machines of his own design a compressor efficiency of nearly .9. Allowing for the somewhat greater friction in the mechanism the total efficiency was found to be about .76. In general then we may take the total efficiency of the single stage compressors usually employed in this country as .5 to .6, very rarely higher, while the best two-stage compressors may give an efficiency slightly in excess of .75. For steady working, .75 would be an excellent result.

We may next look into the action of the compressed air in the mains. As in the case of water, the frictional resistance and consequent loss of pressure varies directly with the square of the velocity of the air and inversely with the diameter of the pipe. By reducing the one and increasing the other the efficiency of the line may be increased at the cost of a con-

siderable increase in original outlay. Any attempt to force the output of the main rapidly increases the losses. At a working gauge pressure of 60 pounds per square inch, which is in very frequent use, the per cent. of pressure lost per 1,000 feet of pipe of various diameters is given in the following table—the velocity being taken at 30 feet per second:

Diameter.........	1"	2"	3"	4"	5"	6"	12"	18"	24"	36"	48"
Per cent. loss......	21.8	10.9	7.8	5.45	4.37	3.66	1.0	0.66	0.5	.33	.25

The friction in the pipes is proportionally greater in small pipes than in large, and this table is taken as correct for the medium sizes. No allowance is made for increase in velocity through a long main, for leakage, nor for draining traps, elbows, curves and other extra resistances, so that as in practice the larger and longer mains suffer the more from these various causes, the table will not be found widely in error for ordinary cases. Very large straight away mains will give somewhat better results, and the five last columns of the table are computed from Riedler's experiments on the Paris air mains, 11¾ inches in diameter and 10 miles long. All losses are included. Losses in the air mains can therefore be kept within a reasonable amount in most cases. With large pipes and low velocities power can be transmitted with no more loss than is customary in the conductors of an electrical system. Small distributing pipes, however, entail a serious loss if they are of any considerable length.

The motor is the last element of pneumatic transmission to be considered. Generally it is almost identical with an ordinary steam engine; in fact steam engines have been often utilized for air, and common rock drills may be used indifferently for steam or air with sometimes slight changes in the packing of the pistons and piston rods. Some special air motors are in use with slight modifications from the usual steam engine type. In most of these the air is used expansively and at a fairly good efficiency. Tests by Riedler on the Paris system show for the smaller air motors an efficiency of as high as 85 per cent. so far as the utilization of the available energy in the air is concerned, or taking into account the

mechanical losses, 70 to 75 per cent. Occasional results as low as 50 to 60 per cent. were obtained even when the air was used expansively, while if used non-expansively the total efficiency was uniformly below 40 per cent. Tests on an adapted steam engine with Corliss valve gear gave a pneumatic efficiency of .90, with a total efficiency of .81. These figures are under more than usually favorable conditions.

One of the principal difficulties with air motors is freezing due to the sudden expansion of the compressed air, and the congelation of any moisture carried with it. It is quite useful therefore to supply to the motor artificially a certain amount of heat, sufficient to keep the exhaust at the ordinary temperature, especially if the air has been cooled by spray during condensation. This heating process is very generally extended so as not only to obviate all danger of freezing but to add to the output of the air motor by giving to the compressed air a very considerable amount of energy. The air is passed through a simple reheating furnace and delivered to the motor at a temperature of about 300° Fahrenheit. The energy delivered by the motor is composed of that actually transmitted through the mains *plus* that locally furnished by the reheater.

The amount of fuel used is not great, usually from $\frac{1}{8}$ to $\frac{1}{4}$ of a pound of coal per horse-power-hour, and the increase of power obtained is about 25 per cent. of that which would otherwise be obtained from the motor. This means that the heat is very effectively utilized. Reheating is not a method of increasing the efficiency of the system as is sometimes supposed, but a convenient way of working a hot air engine in conjunction with an initial pressure obtained from air mains. It increases the operating expense by a very perceptible though rather small amount and gains a good return in power. In so far it is desirable, but it no more increases the *efficiency* of the pneumatic transmission than would power from any other source added to the power actually transmitted.

We are now in a position to form a clear idea of the real efficiency of transmission of power by compressed air. Taking the compressor and motor efficiencies already given and assuming 10 per cent. loss of energy in the mains, we have for the total efficiency from indicated horse-power at the compressor to brake-horse-power at the motor: $.75 \times .90 \times .80 = .54$

for large two-stage compressors and large motors; while with ordinary apparatus it would be about $.70 \times .90 \times .75 = .47$. At half load these figures would be reduced to about .45 and .35 respectively. In operating drills, which are motors in which the air is used non-expansively and to which the air is carried considerable distances through small pipes, the total efficiency is almost always below rather than above .30. The efficiency of .54 given above cannot well be realized without recourse to artificial heating to enable the air to be used expansively without trouble from freezing.

Compressed air has been mainly used for mining operations, where its entire safety and its ventilating effect are strong points in its favor. More rarely it is employed for general power purposes. Of such use the Popp compressed air system in Paris is by far the best example.

This great work started from a system of regulating clocks by compressed air established some twenty years ago. Nearly a decade later the use of the compressed air for motors began, and after several extensions of the old plant the present station was built. It contains four 2,000 HP compound compressors, of which three are regularly used and the fourth held in reserve. The steam cylinders are triple expansion worked with a steam pressure of 180 pounds. The air pressure is 7 atmospheres and the new mains are 20 inches in diameter, of wrought iron. There are in all more than 30 miles of distributing main, most of it of 12 inches and under in diameter. A very large number of motors of sizes from a fan motor to more than 100 HP are in use. Their total amount runs up to several thousand HP, even though the majority of them are less than a single horse-power. Except in very small motors reheaters are used, raising the temperature of the air generally to between 200° and 300° F. The efficiency of the whole system from Professor Kennedy's investigations is about 50 per cent. under very favorable conditions. The prices charged for power have not been generally known but are understood to be somewhat in excess of $100 per horse-power per working year.

IV. In point of convenience and efficiency compressed air is nearer to electricity for the distribution of power over large areas than any other method. The only other system that

approaches them is the transmission of gaseous fuel for use in explosive gas engines. At equal pressures one can send through a given pipe twenty times as much energy stored in gas as in air. A good air motor requires about 450 cubic feet of air at atmospheric pressure per indicated HP hour, while a gas engine will give the same power on a little over 20 cubic feet of gas. But the cases wherein the distribution of gas would be desirable in connection with a transmission over a long line of pipe are comparatively few. Particularly this system has no place in the development of water powers, the most important economic function of electrical transmission. Nevertheless it must be admitted that for simple distribution of power a well designed fuel gas system is a formidable competitor of any other method yet devised, particularly in the moderate powers—say from 5 to 25 HP.

We are now in a position to review the divers sorts of power transmission that have been discussed, and to compare them with power transmission by electricity.

Without going deeply into details, which will be taken up in due course, we may say that electrical machinery possesses one advantage to an unique extent—high efficiency at moderate loads. Machinery in which the principal losses are frictional is subject to these in amount nearly independent of the load; hence the efficiency drops rapidly at low loads. In dynamos, motors, and transformers, however, the principal losses decrease rapidly with the load, so that within a wide range of load the efficiency is fairly uniform. Fig. 21 gives the efficiency curves for a modern dynamo, motor, and transformer. The generator curve is from a large 500-volt direct-current machine, the motor curve from a smaller machine of the same type, and the transformer curve from a standard type of about 30 kilowatts capacity. In the generator curve the variation of efficiency from half load to full load is less than 2 per cent., in the motor only 2½ per cent., and in the transformer just 1½ per cent. In addition, the efficiency of all three at full load is very high. Hence, not only is an electrical power transmission of great efficiency if the loss in the line be moderate, but this efficiency persists for a wide range of load. As in hydraulic and pneumatic transmission, the efficiency of the line depends on its dimensions; so that by increasing

the weight of copper in the line, the loss of energy may be decreased indefinitely. And since the loss of energy in the line diminishes as the square of the current, the percentage of loss at constant voltage diminishes directly with the load.

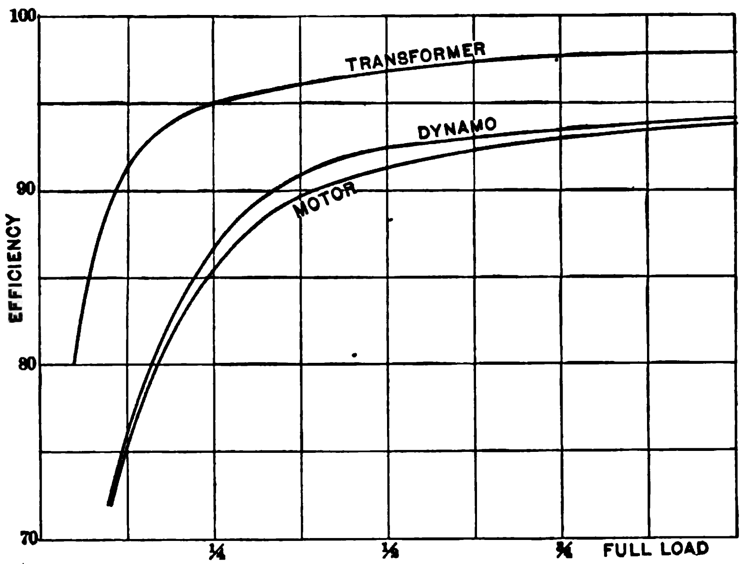


FIG. 21.

Hence the total efficiency may be constant or even increase from half load to full load, even with a quite moderate loss in the line. In pneumatic and hydraulic transmission this condition may occur, but only with large loss in the mains, since the efficiency of the generator and motor parts of these systems decreases too rapidly to be compensated by the gain in the main, unless its efficiency is low at full load. Hence, for ordinary cases of distribution in which the average load is considerably less than full load, often only ⅓ to ½ full load, electric transmission has a very material advantage over all other methods. To appreciate this fully we need only to run over the details of electrical power transmission and compare the results with those which we have obtained for the other methods described.

There are to be considered in electrical power transmission, as in transmission of every sort, two somewhat distinct problems:

First, the transmission of energy over a considerable distance and its utilization in one or a few large units.

Second, the distribution of power to a large number of small units at moderate distances from the centre of distribution. This latter case may sometimes also involve the transmission of power to a real or fictitious centre of distribution. This second problem is the commoner and, while not so sensational as the transmission of power at high voltage over distances of many miles, is of no less commercial importance.

We have all along been considering, in treating of transmission of power by ropes and by hydraulic and pneumatic engines, the case first mentioned, excepting in so far as some special distributions have been referred to. We have already the data for figuring the efficiency of an electric power transmission with large units. In cases of this kind the distance between the generator and motor is likely to be much greater than in the case of distribution to small motors from some central point, and the loss in the line, the only uncertain figure in the transmission, would generally range from .5 to 10 per cent. In case of distributing plants intended to furnish from a single point small units of power over a moderate distance, it is generally found that losses in the line of from 2 to 5 per cent. do not involve excessive cost of copper. In cases where a distribution is coupled with the transmission of power to the central point, the loss from the distant generator to the motors is in most cases from 10 to 15 per cent.

Taking up first the transmission of power from one or more large generators to one or more large motors, we may take safely the commercial efficiency of the generator as that given by the curve, Fig. 21, and that of the motors as at least as good as that given for a motor in the same figure. The efficiency of the line for moderate distances may be taken as 95 per cent. It should be noted that the efficiencies of large alternating generators and motors do not differ materially from those shown; in fact, are quite as likely to be above them as below them. We thus have for the efficiency in a transmission of this kind: $94 \times 95 \times 93 = 84$ per cent. This is largely

in excess of that which could be obtained at distances of say a couple of miles by any other method of transmission.

Even more extraordinary is the efficiency at half load in this case, which is $92 \times 97\frac{1}{2} \times 91 = 81.6$ per cent. It should be borne in mind that these efficiencies are taken from experiments with standard machines, and the efficiencies are those which can be realized in practice. These results show the great advantage to be derived from electrical transmission when, as in most practical cases, full load is seldom reached. It is most important for economical operation to employ a system which will give high efficiency at low loads, and it would be worth while so to do even if the efficiency at full load were not particularly good. With electrical machinery, however, there is no such disadvantage. Even at one-fourth load the efficiency of the electrical system still remains good. It is nearly 73 per cent. on the assumed data. The efficiencies thus given are from the shaft of the generator to the pulley of the motor inclusive.

In the case of distributed motors supplied from a central point not very distant from any of them, the efficiencies of generator and line remain about as before, but the motor efficiencies for the sizes most often employed are below that just given. The average motor efficiency is largely dependent on the skill with which the units are distributed. It has often been proposed to drive separate machines by individual motors, while in other cases comparatively long lines of shafting are employed, grouping many machines into a dynamical unit operated by a motor. To secure economy it is desirable on the one hand to use fairly large motors well loaded, on the other hand the losses in shafting and belting must be kept down.

The larger the motors, the better their efficiency at all loads and the less the average cost per HP, but with small motors the cost and inefficiency of shafts and belts may be in large measure avoided. The most economical arrangement depends entirely upon the nature of the load. Much may be said in favor of individual motors for each machine, but so far as total economy is concerned, this practice is best limited to a few cases—machines demanding several HP (say 5 or more) to operate them, machines so situated as to neces-

sitate much loss in transmitting power to them, and certain classes of portable machines. In applying electric power to workshops already in operation the group system will usually give the best results, individual motors being used only for such machines as might otherwise cause serious loss of power. The following table gives the average full load efficiencies that may safely be expected from motors of various sizes, irrespective of the particular type employed.

HP of motor......	1	3	5	7½	10	15	20	25	40	50	75
Per cent. efficiency	72	78	81	83	85	86	87	88	90	90	91

These are commercial efficiencies reckoned from the electrical input to the mechanical output at the pulleys. Below 5 HP the efficiencies fall off rapidly. At partial loads the efficiencies are somewhat uncertain, inasmuch as some motors are designed so as to give their maximum efficiency at some point below full load, while others work with greater and greater efficiency as the load increases until heating or sparking limits the output. The former sort are most desirable for ordinary workshop use, while the latter are well suited to intermittent work at very heavy loads, as in hoisting. The difference in the two types of machine is very material. It is easily possible to procure motors that will not vary more than 5 per cent. in efficiency from full load to half load, and this even in machines as small as 2 or 3 HP. We may now calculate the efficiency of an electric distribution with motors of moderate size—such a case as might come from the electrical equipment of large factories. The generator efficiency may be taken as before at .94 and that of the line at .95, while the motors must be taken close account of in order to estimate their collective efficiency. Assuming the sizes of motors in close accordance with those in several existing installations of similar character, we may sum them up about as follows:

5 .... 3 HP
5 .... 5 HP
10 .... 10 HP
10 .... 20 HP
5 .... 25 HP
2 .... 50 HP

In all 37 motors aggregating 565 HP. The mean full load efficiency of this group is very nearly .87. The efficiency of the system is then

$$.94 \times .95 \times .87 = 77.6.$$

This result requires full load throughout the plant, a somewhat unusual condition with any kind of distribution. From the data already given the half load efficiency should be about

$$.92 \times .975 \times .82 = .735.$$

Between the limits just computed should lie the commercial efficiency of any well-designed motor distribution reckoned from the dynamo pulley. In the case of steam-driven plants it is often desirable to consider the indicated HP of the engine as the starting point, and the question immediately arises as to the commercial efficiency of the combination of dynamo and engine. In cases where high efficiency is the desideratum direct coupling is usually employed, saving thereby the loss of power, perhaps 5 per cent., produced by belting. The losses in such direct-coupled units vary considerably with the size and type of both machines. Fig. 22 shows the efficiency of two such combinations at various loads. Curve *A* is from an actual test of the combination; curve *B* from tests of an engine and dynamo separately. Each unit was of several hundred HP. The high result from curve *A* is mainly due to very low friction.

These curves give handy data for computing the total efficiency of a motor plant from the motor pulleys to the indicated horse-power of the driving engine. Taking the combined engine and dynamo efficiency from *A* and assuming the same figures as before on motors and line we have at full load

$$.88 \times .95 \times .87 = .727.$$

And from the same data at half load

$$.78 \times .975 \times .87 = .651.$$

For certain computations, as in case of figuring out a complete installation, the above efficiencies are convenient. They show that in very many instances the distribution of power by electric motors is very much more economical of energy than any other method employed. In ordinary manufacturing operations power is generally transmitted to the working machines through the medium of lines of shafting of greater or less length. These are very rarely belted direct to the

machines, but transfer power to them through one or more countershafts. Often the direction of shafts is changed by gearing or quarter turn belts, and even when the power is distributed through only a single large building there will be found more often than not intervening between the driving engine and the driven machine three belts and two lines of shafting of considerable length, and not infrequently still other

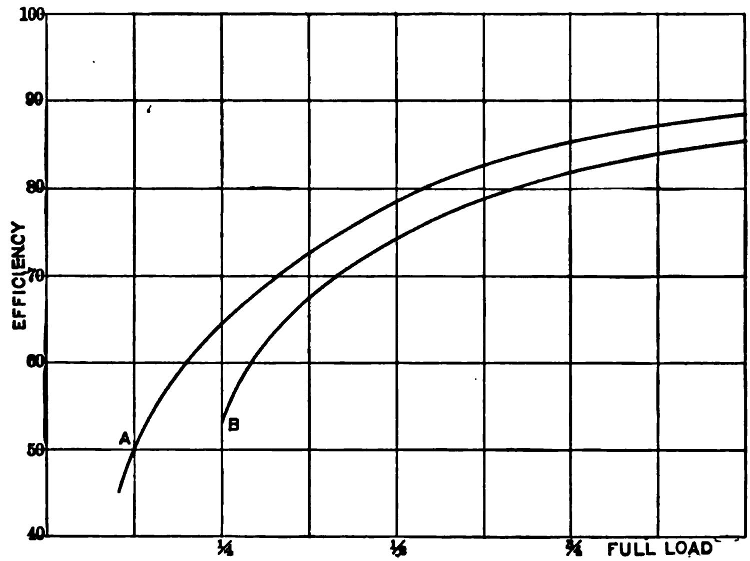


FIG. 22.

belts and shafts. It very often happens, too, that to keep in operation one small machine in a distant part of the shop it is necessary to drive a long shaft the friction of which consumes half a dozen times as much power as is actually needed at the machine. The constant care required to keep long lines of shafting in operative condition is an irritating and costly concomitant. The necessary result is a considerable loss of power, which being nearly constant in amount is very severe at partial loads.

Allowing 5 per cent. loss of energy for each transference of power by belting, a figure in accordance with facts, and 10 per cent. loss for each long line shaft driven, it is sufficiently evident that from 20 to 25 per cent. of the brake-horse-power

delivered by the engine must be consumed even under very favorable circumstances by the belting and shafting at full load. This means an efficiency at half load of from 50 to 60 per cent. only, and at lesser loads a very low efficiency indeed.

The large number of careful experiments carried out on shafting in different kinds of workshops, and under various conditions, shows that only under very exceptional circumstances is the loss of power by shafting between the engine and the driven machines as low as 25 per cent. Far more often it is from 30 to 50 per cent., and sometimes as high as 75 or 80 per cent. The figures, which have been well established, regarding the efficiency of the transmission of power by motors, show that at full load it is comparatively easy to surpass 75 per cent. efficiency; thus more than equaling the very best results that can be obtained with shafting. At half load and below, the advantage of the electric transmission becomes enormous, even supposing shafting to be at its very best.

Compared with ordinary transmission by shafting, the motor system is incomparably superior at all loads, so that it may easily happen that a given amount of work can be accomplished through the medium of a motor plant with one-half the steam power required for the delivery of the same power through shafts and belts. Such results as this have actually been obtained in practice. It is therefore safe to conclude that the distribution of power by motors is, under any ordinary commercial conditions, at least as efficient as the very best distribution of power by shafting at full load and much more efficient at low loads. Under working conditions in almost all sorts of manufacturing establishments, light loads are the rule and full loads the rare exception; consequently the results of displacing shafting by motor service have, as a rule, been exceedingly satisfactory in point of efficiency, and the lessened operating expense more than offsets the extra cost of installation.

In one large three-phase plant, that of Escher, Wyss & Co. at Winterthur, Switzerland, 300 HP in 32 motors worked from a 12-mile transmission line displaced far greater capacity in steam engines, and similar results on a smaller scale are not uncommon.

To add force to this comparison between the efficiency of

shafting and of motors, the following results from electrical distribution plants already installed may be pertinent. One of the best known of all such transmissions is that at the fire-arms factory at Herstal, Belgium. There are there installed 17 motors of an aggregate capacity of 305 HP, driven by a 300-KW generator direct coupled to a 500 HP compound condensing engine. The efficiency guaranteed from the shaft of dynamo to the pulleys of the motors is 77 per cent. Since its first installation, the plant has been increased by the addition of a second direct-coupled dynamo and the total horse-power of motors is 428. A second notable installation of motors in the same vicinity is at the metallurgical works of La Société de la Vielle-Montagne, consisting of a 375 KW 500-volt dynamo direct driven at a speed of 80 revolutions per minute by a 600 HP compound condensing engine. The plant consists of 37 motors with an aggregate HP of 329. The full load efficiency of the plant from dynamo shaft to motor pulley is 76 per cent. The loss in the lines, both in this case and in the preceding, is very small, only 2 per cent. They are both typical cases of transmission to motors driving groups of machines, and in spite of rather low dynamo efficiencies at full load, these being in each case 90 per cent., the results obtained are in close accordance with those already stated as appropriate to similar cases. As an example of work under somewhat more favorable conditions, the three-phase power plant at Columbia, S. C., may be instanced.

The problem here undertaken was to drive a very large cotton mill, utilizing for the purpose a water power about 800 feet distant. Two 500-KW dynamos direct coupled at a speed of 108 turns per minute deliver current at 550 volts to an underground line connecting the power station with the mills. The motors are suspended from the ceiling and each drives several short countershafts. The motors are wound for the generator voltage without transformers, and are of a uniform size, 65 HP each. The commercial efficiency of this plant, taken as a whole from the shaft of the dynamo to the pulleys of the motors, is not less than 82 per cent. at full load. This good result is due to the use of large motors, and to the small line loss of 2 per cent. as in the preceding foreign examples. These results are thoroughly typical, and can regularly

be repeated in practice. Even smaller plants can be counted on to give nearly or quite as good results, since the difference in efficiency, supposing motors of the same size to be used, between a dynamo of 100 KW and one of 400 or 500 KW is hardly more than 1 per cent. at full load, supposing machines of the same general design to be employed, nor is there any substantial difference in efficiency between plants employing direct current and those using polyphase apparatus, as may be judged from the figures just given.

We are now in position intelligently to compare the transmission and distribution of power by electric means with the other methods which have sometimes been employed.

All comparisons between methods of transmitting power have to be based in a measure on their relative efficiency. Now in every such method there are three essential factors: 1st, the generating mechanism, which receives power direct from the prime mover and in conjunction with which it is considered; 2d, the transmitting mechanism, which may be an electric line, a pipe line, ropes, or belts, and 3d, the motor part of the transmission, which receives power from the transmitting mechanism and delivers it for use. For a given capacity of the generating and receiving mechanisms, the efficiency of each at all loads is determined within fairly close limits. The transmitting mechanism, however, is not so closely determined, save in the case of the rope drive.

Electric, pneumatic and hydraulic transmission lines are all subject to the general principle that the loss in transmission can be made indefinitely small by an indefinitely large expenditure of capital, enormous cross-section in the one case or huge pipe lines in the others. The efficiency of these methods is therefore a fluctuating quantity depending on that loss in the transmitting mechanism which may be desirable from an engineering or economical standpoint. In making comparisons between these methods, there is a wide opportunity for error unless some common basis of comparison is predetermined. In the next case any such comparison must differ widely in its results according to the character of the power distribution which is to be attempted. We have already seen that with the rope drive distribution is very difficult, while with electric and pneumatic systems it is comparatively easy.

A general valuation of the commercial possibilities of these divers matters is therefore hard to make except in a general way. We can, however, by assuming a given transmission of given magnitude and character, and further assuming such loss in the transmitting mechanism as might reasonably be expected in practice, arrive at a reasonably accurate conclusion for the case considered. As a very simple example of power transmission, let us take the delivery of power over a distance of two miles, the delivery being in one unit or at most two units. We will assume the same indicated HP furnished at the generating end of the line in each case, of which as much as possible is to be delivered at the receiving station, the losses in transmission being taken as 10 per cent. of the power delivered to the line; this is to cover all losses of energy by resistance and leakage on the electrical line or loss of pressure and resulting expenditure of energy, leakage, friction and all other sources of loss in the other cases.

As the same indicated power is generated in each case, we will suppose a modern plant with compound condensing engines costing complete with buildings $50 per HP. We will further assume that each indicated horse-power per working year of 3,000 hours will cost $18; this covering all expenses except those chargeable to interest and depreciation. For this simple case we have the following costs of initial plant and of operation per mechanical horse-power delivered from the motor, full load only being considered. The four methods considered are rope driving, pneumatic, pneumatic with reheating apparatus at the motors, and electrical. The prices are from close estimates of the cost in each case. The dynamos are supposed to be direct coupled. The compressors to be direct acting, two-stage compressors. The steam cylinders Corliss compound condensing type. The air pressure assumed is 60 lbs. above atmospheric pressure. The electric voltage 3,000. The rope speed about one mile per minute. Interest and depreciation are taken at 10 per cent. of the total cost of the plant, save in the case of the rope drive, where an additional charge for renewal of cable is made on the supposition that the cable will last somewhere from 18 months to 2 years, which is fully as favorable a result as can fairly be expected. The following are the comparative estimates:

ROPE, EFFICIENCY 67 PER CENT.

COST.

Steam plant,	$50,000
Pulley stations,	25,000
Cables, steel,	17,000
Total cost,	$92,000

OPERATING EXPENSE.

1,000 I.HP at $18,	$18,000
Interest and depreciation on plant, at 10 per cent.,	7,500
Depreciation of cable,	8,000
	$33,500

Net HP produced, 672.
Cost per HP-year, $49.

PNEUMATIC, EFFICIENCY 54 PER CENT.

COST.

Steam plant excluding engines,	$35,000
Compressors,	17,000
Air mains laid, 12 inches,	18,000
Air motors,	12,000
Total cost,	$82,000

OPERATING EXPENSE.

1,000 I.HP at $18,	$18,000
Interest and depreciation, at 10 per cent.,	8,200
	$26,200

Net HP delivered, 540.
Cost per HP-year, $48.

AIR REHEATED, APPARENT EFFICIENCY 65 PER CENT.

COST.

Steam plant, excluding engines,	$35,000
Compressors,	17,000
Air mains laid,	18,000
Air motors and reheaters with chimney, etc.,	14,000
Total cost,	$84,000

OPERATING EXPENSE.

1,000 I.HP at $18,	$18,000
Interest and depreciation, at 10 per cent,	8,400
Coal and labor for reheating,	1,500
	$27,900

Net HP delivered, 650.
Cost per HP year, $43.

ELECTRIC, EFFICIENCY 73 PER CENT.

COST.

Steam plant,	$50,000
Dynamos,	18,000
Line,	3,000
Motors,	13,000
Total cost,	$84,000

OPERATING EXPENSE.

1,000 I.HP at $18,	$18,000
Interest and depreciation, at 10 per cent,	8,400
Electrician,	1,500
	$27,900

Net HP, 730.
Cost per HP-year, $38.

It appears at once that the rope drive is beyond the range of its efficient use. Its first cost is greater than that of either of the other methods and the expense is carried to a very high figure by the item of depreciation on the cables, which cannot be avoided, hence in spite of a high efficiency the cost per HP year delivered rises to $49. We may next consider the schedule of cost for the pneumatic system. In this case the most formidable item is the cost of the air mains, which should be at least 12 inches in diameter. Nevertheless the total initial cost is the lowest of the four. The operating expense is also the lowest, but the very low efficiency of the pneumatic system without reheating raises the cost per HP delivered to a very considerable amount; almost as much as in the case of the rope drive. Reheating would almost always be used in connection with a plant of this size, and with reheating the result is much more favorable. The initial expenditure is somewhat increased by the addition of the reheaters, piping and chimney. The operating expense is also slightly increased by the coal necessary for reheating, taken at ¼ of a pound per HP per hour and the small amount of additional labor involved in caring for the reheaters, disposing of the ashes and looking after the reheating plant generally. The apparent efficiency in this case is very excellent, 65 per cent. being reasonably attainable, and the cost per HP year falls to $43, showing conclusively enough the advantage of reheating; at least where

the units are so large that the presence of a reheater is not a practical nuisance.

Finally, we come to the electric power transmission. In this case the most striking feature is the low cost of the line, supposed here to be overhead. It may be noted, however, that an underground line, consisting of cable laid in conduit, still leaves the cost per HP year lower than that of any of the other methods. Operating expense is fairly increased by the addition of an electrician to the cost of the indicated horse power, interest and depreciation. The total first cost is practically the same as that of air with reheater, as is also the operating expense. The added efficiency, however, brings the cost per HP year to $38; decidedly the lowest of the four cases considered. It may be thought that difference of loss in transmission might possibly alter the relation of the electric plant to the air plant with reheaters, but an added efficiency of line would in either case be accompanied by added expenditure of not very different amounts in the two cases, and the efficiency of the electric plant would always be enough higher than that of the air plant to give it the advantage in net cost per HP, however the two plants might be arranged. We thus find that at a distance of two miles the electric transmission has a material advantage, air with reheaters, air without reheaters, and rope drive following it in the order named. As previously mentioned at a distance of one mile the efficiency of the rope drive is so far increased as to bring the cost per HP delivered down nearly to that of the electric transmission. The pneumatic method would at the distance of one mile, as may readily be computed, take about the same relative position as before, since the efficiency of the two maintains approximately the same relation to the others.

The pneumatic plant gains in first cost at this lesser distance, not enough, however, to alter the final result. At half a mile distance, the rope drive will be found to be the cheapest in first cost and also, through its enormous efficiency, to be the cheapest per HP delivered, in spite of the large depreciation in the cables, while the electric and pneumatic systems would be very close together, the electric, however, still retaining a slight advantage due to its great efficiency.

Neither can in point of absolute cost of power delivered compete with the rope drive at this distance for this large and simple transmission. Figures that have heretofore been given on the relative cost and efficiency of such transmissions have as a rule been in error in two very essential particulars: first, the efficiencies of the electrical system have been greatly underestimated owing to the poor machines with which the first experiments were made; second, the commercial advantage of reheating in the pneumatic transmission has not generally been given its proper weight. It is, as has been already stated, not a method of increasing the efficiency but of increasing the power delivered by addition of energy at the receiving end of the line under very favorable conditions. The figures just given are believed to be as nearly exact as present conditions permit. The hydraulic system has not been here considered inasmuch as it is not of general applicability.

At less than full load and hence under variable loads the electric system enjoys the unique advantage of having the losses of energy in every part of the system decrease as the load decreases, while in rope driving all the losses are practically constant, and in the hydraulic and pneumatic systems all are nearly constant save that in the pipe line.

Hence under low and varying loads electric transmission has a great additional advantage. Since in distributions of power employing a considerable number of motors light load on the motors is the invariable rule, as soon as we depart from the very simple case discussed the electrical system gains in relative economy at every departure. These more general cases have already been described, and gathering the results we may construct the following table, showing the efficiency of each system under full and half loads:

SYSTEM.	FULL LOAD.	HALF LOAD.
Wire rope	68	46
Hydraulic high pressure	53	45
Hydraulic low pressure	50	50
Pneumatic	50	40
Pneumatic reheated (virtual efficiency)	65	50
Electric	73	65

The efficiencies in the electric system as here given are lower than could be reached practically in large plants.

All the figures must be taken as approximate. They are under conditions fairly comparable except in case of the low pressure hydraulic system, in which the large proportion of loss due to pipe friction operates to hold up the half load efficiency to an abnormal degree. With the ordinary proportion of small motors this half load efficiency would be nearer 40 than 50 per cent. The electric system is easily the most efficient at any and all loads. Of the others, wire rope transmission, if the distributed units are fairly large, holds the second place for short distances, and the pneumatic system with energy added at the motors by reheating, at moderate and long distances. Without reheating it occupies the last place in order of efficiency, although even so, it is, next to electricity, the most convenient method of distributing power.

In fact, electricity and compressed air are the only two systems available for the general distribution of energy, and also the most used. The Popp air system in Paris is, save for some electric central stations, the largest power distributing plant in the world. The Edison system in New York city has, however, about 10,000 HP, in motors operated from its mains, and other similar stations have loads of several thousand HP. Of course the very largest power stations are those belonging to electric railway systems in the largest American cities. Several of these exceed 10,000 HP in generator capacity and frequently in actual output, notably the systems in Boston, Brooklyn and Philadelphia. Recent advances in electrical engineering, particularly the effective utilization of alternating currents, have greatly cheapened the distribution of electrical energy, and other systems are now seldom installed for ordinary purposes. A few pneumatic and hydraulic plants will continue to be used owing to the large capital already invested in them, but new work is, and in the nature of things must be, almost exclusively electrical. As the transmission of power from great distances becomes more common and the radii of distribution themselves increase, the electrical methods gain more and more in relative value, and all others become more inefficient and impracticable.

We have now discussed in some detail the sources of natural energy which are available for human use, and the most prominent of the systems employed for their utilization. We have found that for practical purposes steam power and water power must at present be used to the virtual exclusion of all others, the former perhaps less than the latter save for distribution of power over short distances.

Of the methods of distribution we have found all save compressed air and electricity limited in their application, the hydraulic systems to special classes of work under favorable topographical conditions, and rope transmission limited to short distances and small numbers of power units delivered. Both are noticably inefficient. The pneumatic system is very general in its applicability, but of very low intrinsic efficiency. When used in connection with reheating apparatus it requires additional care, and the motors like steam engines are heavy and inconvenient. The electric system on the other hand employs motors which are compact and efficient, run practically without attention, and can be placed in any situation or position that is convenient. Furthermore in average working efficiency the electric system is 10 to 15 per cent. higher than any other yet devised, so that it is more economical in use at nearly all distances and under nearly all conditions. Finally it unites with power distribution the ability to furnish light and heat, thus gaining an immense commercial advantage. This advantage is shared only by gas transmission, which up to the present time remains of doubtful value on account of the cost of the motors, their rapid depreciation and their inefficiency at moderate loads. Having now overlooked its advantages in general, it is proper to pass to the details of the methods employed for its utilization and thence to the general problem of its economical generation, transmission and distribution.

CHAPTER III.

POWER TRANSMISSION BY CONTINUOUS CURRENTS.

UP to the present time by far the largest part of electrical power transmission has been done by continuous currents. All the earlier plants were of this type, and even now, when transmission by alternating currents, polyphase and other, is pushing rapidly to the front, the older type of apparatus is still being installed on an extensive scale, and on account of the large number of plants now in operation, even if for no other reason, will probably remain in use for a long time to come. New power transmission plants, both here and abroad, are more and more frequently installed for alternating currents, and in many cases this practice is almost absolutely necessary, but there still remain many cases wherein the conditions are as well or better met in the old-fashioned way.

Chief among these may be mentioned electric railway work, which in America alone probably requires more than a full million horse power in generators and motors. Certain difficult work at variable speed and load, and many simple transmissions over short distances, are at present best handled by continuous current machinery. As alternating practice advances many, perhaps all, of these special cases will be eliminated, but we are dealing with the art of power transmission as it exists to-day, and hence continuous current working deserves very careful consideration.

The broad principle of the continuous current generator has already been explained, but its modifications in actual work are important and worthy of special investigation. In a general way, continuous currents are almost always obtained by commuting the current obtained from a machine which would naturally deliver alternating currents. This process is, however, by no means as simple as Fig. 9 would suggest. With a two-part commutator the resulting current, although unidirectional, would necessarily be very irregular owing to the fact

that the total current drops to zero at the moment of commutation. Such a current is ill fitted for many purposes, and the commutator would be rapidly destroyed by sparking if the machine were of any practical size.

To avoid these difficulties, the number of coils on the armature is increased, and they are so interconnected that, while each coil has its connection to the outside current reversed as before, when its electromotive force is zero, the other coils in which the E. M. F. still remains in the right direction continue in circuit unchanged. In this way the E. M. F. at the brush is the sum of the E. M. Fs. of a number of coils, each of which is reversed at the proper moment. The number of commutator segments is increased proportionally to the number of coils,

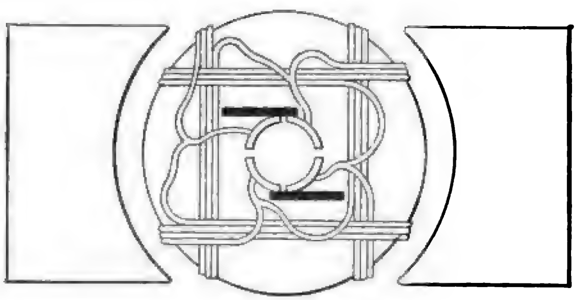


FIG. 23.

and the commutator thus becomes a comparatively complicated structure. The result, however, is that the total E. M. F. of the armature cannot vary by more than the variation due to a single coil. The nature of this modification is shown in Fig. 23, which shows a four-part commutator connected to a four-coil drum armature.

An eight-part winding of modern type is shown in Fig. 24. Tracing out the currents in this will give a clear idea both of a typical winding and of the process of commutation.

In commercial machines the number of individual coils and of commutator segments often exceeds 100, but the principle of the winding is the same. Nearly all the early dynamos had several turns of wire per coil, as in Fig. 23, but at present, in many large machines, one turn constitutes a complete coil. This extreme subdivision is to avoid sparking at the commu-

tator, which becomes destructive if the current be large and the E. M. F. per commutator segment great.

If each coil generates a considerable voltage, there is even under the best conditions of commutation a strong tendency for sparks to follow the brush across the insulation between segments, or even to jump across this insulation elsewhere. As this goes from bad to worse and rapidly ruins the commutator, every precaution has to be taken against such a contingency. The E. M. F. generated by each coil is kept low by subdividing the winding, and in large machines it is the

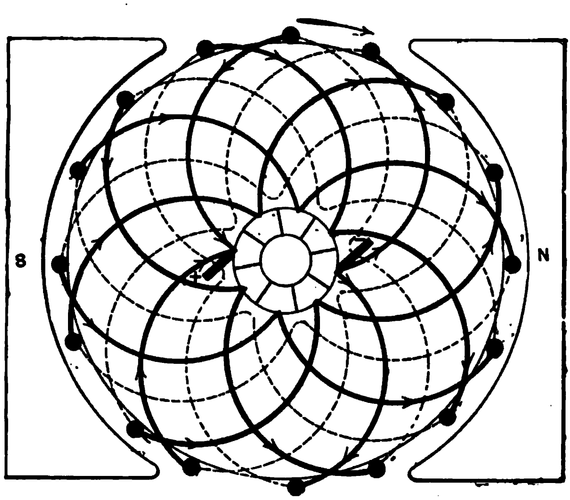


FIG 24.

rule that the E. M. F. of a single loop is quite all that can safely be allotted to a single commutator segment.

Present good practice indicates that for generators for lighting up to 100 or 150 volts the voltage between brushes should be subdivided so that it shall not exceed 3 or 4 volts for each segment between the brushes. For 500 or 600 volt machines it should not ordinarily exceed about 10 volts, while for dynamos of moderate output and even higher voltage it may rise to 20 volts or more.

The reason for these different figures is that the destructiveness of the spark depends on the amount of current which is

liable to be involved. On a low voltage commutator intended for heavy currents, even very moderate sparking may gnaw the segments seriously, while the spark of an arc machine in spite of its venomous appearance may do very little harm, as the maximum current in the whole bar will not exceed 8 or 10 amperes. Consequently the voltage per bar in such cases is sometimes 50 or more, while in very large incandescent machines and in those designed for electrolytic purposes the E. M. F. per bar is often less than 2 volts or even below 1 volt.

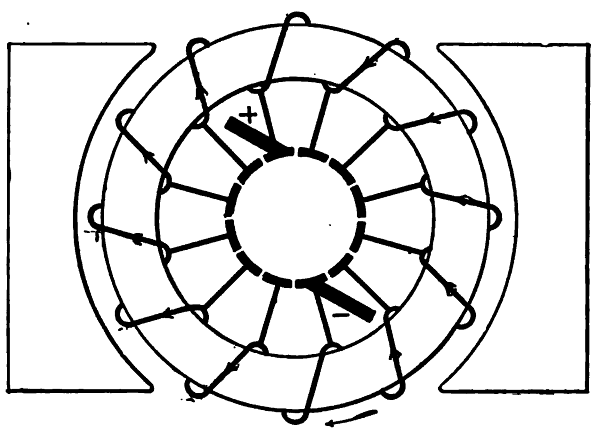


FIG. 25.

Windings like those of Figs. 23 and 24 are of the so-called *drum* type, in which each convolution extends around the whole body of the armature, either diametrically or nearly so. Another sort of armature winding frequently used, although less now than formerly, is the *Gramme*, so called from its inventor. Here the iron body of the armature is, instead of being cylindrical, in the form of a massive ring of rectangular cross section. The windings are looped through and around this ring, fitting it firmly and closely. Fig. 25, which shows in diagram a winding in ten sections, furnishes a good example of the Gramme construction. There may be one or several turns per coil, as in drum windings. These two general types of windings are used with various modifications in nearly all continuous current dynamos. Each has its good

and bad features. The Gramme winding makes it very easy to keep down the voltage per segment, inasmuch as for each external armature wire there is a commutator bar, while in the drum form there is but one bar for two wires. It is also mechanically solid even when wound with small wire, and no two adjacent wires can have a considerable voltage between them, thus making it easy to build an armature for high E. M. F. On the other hand, the drum winding gives a very compact armature of easy construction, and the magnetism induced in it is less likely to disturb that of the field.

In the small machines once usual the Gramme type was preferred for high voltages on account of the ease with which it could be repaired, while the drum was liked for its simplicity of mechanical construction as a whole and excellent efficiency as an inductor. In modern practice the differences between these types have become much less marked. With large units, particularly of the multipolar form now usual, the drum winding is as easily insulated as the Gramme, for with the winding now used in such cases there need be no considerable voltage between adjacent wires, and repairs are of very infrequent occurrence. In fact, the drum winding can be made quite as accessible as the other, and is on the whole cheaper and simpler. Almost the sole advantage of the Gramme (*or ring*) winding is that of low voltage per commutator bar. Mechanically, too, there is less difference than formerly, for the coils are in both types frequently bedded in slots in the iron of the armature core.

It must be noted that the armature of the modern dynamo, unless of small size or unusually high voltage, is seldom wound with wire in the ordinary sense of the word. Instead, the conductors are bars of copper, usually of sections rectangular rather than round, and generally lacking any permanently attached insulation. Whatever the winding, the conductors on the armature face are inclosed in close fitting tubes of mica and specially treated paper or the like, and then put in place on the armature core or in more or less completely closed channels cut in it. If on the core surface, the bars are often not insulated on the exterior surface at all. If the armature core be slotted, the insulating material is preferably put in position first and the bar put in afterward. As to the rest

of the winding it is completed by connectors of copper strip or rod soldered to the face conductors and insulated in a substantial manner. Thus each convolution, whether of ring or drum winding, is composed of from two to four pieces.

A typical modern ring winding is shown in Fig. 26. It well exemplifies the construction above mentioned, and in this case the insulated faces of the exterior conductors form the commutator of the machine. Such a construction of course excludes iron clad armatures and is best fitted for a machine having a field magnet inside the ring armature. A similar

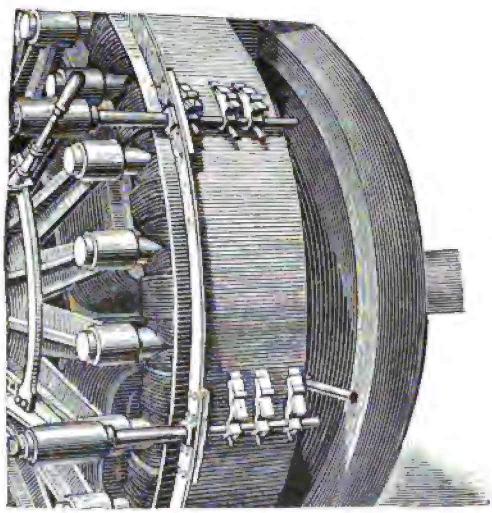


FIG. 26.

arrangement which avoids the above limitations, uses the side connectors of the ring as commutator segments. The general principle, however, is the same, whether the commutator forms part of the winding proper or is a separate structure.

An iron clad drum winding of typical character is shown in Fig. 27. Here the exterior bars are fitted into thoroughly insulated slots in the core, and wedged firmly into place by insulating wedges. Sometimes the bars themselves are shaped so as to act as wedges. In either case the bars are held almost as solidly as if they formed an integral part of the core. The commutator in these windings must be a separate affair. Fig.

27 shows well the nature of the winding, with its slotted core, ventilating spaces, and massive bars—in this example 4 per slot. The end connectors lie in a pair of reverse spirals, one outside the other, and separated by firm insulation. The relation of these connectors to the rest of the winding is illustrated in Fig. 24.

Between the modern drum and ring armatures it is difficult to discriminate. Both have been successfully used in dynamos of the largest size, but the iron clad drum is in the more general use. It is rather unusual to find a standard generator of recent build of 100 KW or more output with a regular wire wound armature, and the most of them have some modification of the bar windings just described.

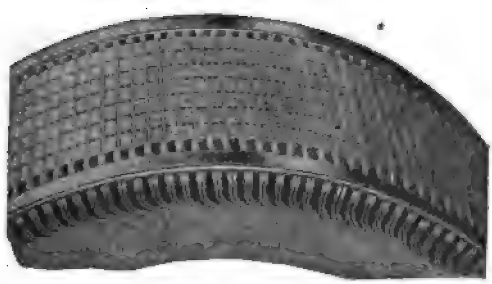
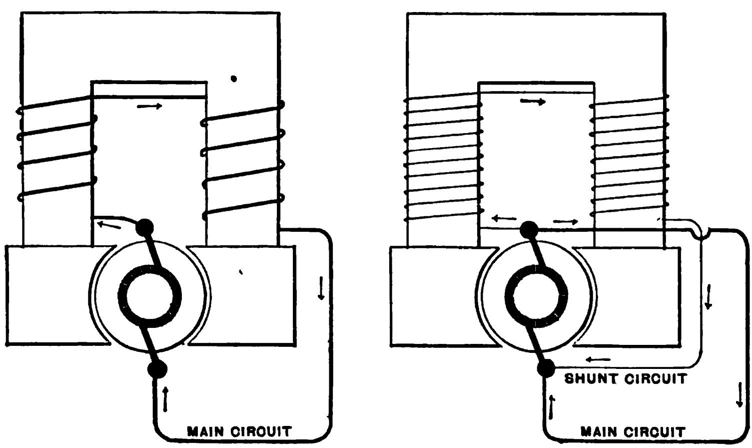


FIG. 27.

We have briefly reviewed here the armature windings at present in general use and may now pass to the various windings employed for the field magnets. These are, in continuous current dynamos, almost always connected with, and supplied with current from, the armature winding, thus making the machines self-exciting. As the armature is turned the action begins with the weak residual magnetism left in the field magnets, and the current set up by the small E. M. F. thus produced is passed around and gradually strengthens the magnets, building them up to full strength. If this residual magnetism is very feeble, as may happen when it is knocked out of the iron by rough handling or the continual jarring of a long journey, it is sometimes quite difficult to get the machine into action.

The simplest form of field winding, and the one which was most extensively used at first, is that in which the current from

one of the brushes passes around the field magnet coils on its way to or from the external circuit of the machine, as shown in Fig. 28. This *series* winding possesses more than one advantage. It consists of a comparatively small number of convolutions of rather large wire and so is cheap to wind; it is, for this same reason, little liable to injury and easy to repair when injured; and what is of particular importance, whenever the series dynamo is called upon for more current, the magnetizing power of the field is raised by the increase, thus increasing the electromotive force. This property, once considered a disadvantage, becomes of great value in modern



FIGS. 28 AND 29.

windings adapted for the purpose. As the generation of E. M. F. at the start depends entirely on the residual magnetism, series wound machines do not "build up" full voltage very easily unless the resistance of the outside circuit is fairly low, thus giving the current a chance.

The common shunt winding shown in Fig. 29 almost describes itself. The brushes are, independently of the exterior circuit, connected to magnetizing coils of fine wire. Although such a field winding is slightly harder to construct and to maintain, it produces a magnetic field that is relatively free from any actions in the working circuit of the machine. So long as the E. M. F. at the brushes is unaffected by changes of speed, the field will

be quite steady except as a very large current in the exterior circuit may reduce the voltage available for the field by causing a loss of voltage in the armature. If the armature resistance be very small, there will be almost a constant E. M. F. at the brushes except as the current flowing in the armature may produce a magnetization opposed to the shunt field. For a considerable time, then, the shunt winding was always used when a constant E. M. F. was required. At the same time, it permits the E. M. F. to be varied, if desired, with a very small loss of energy, by the simple expedient of putting a variable resistance in circuit with the field magnets.

As the principles of dynamo construction became better known, it was apparent that the above method of getting a constant E. M. F. was rather expensive. To build an armature that would carry a heavy current without noticeable loss of voltage and to inclose it in fields so strong as to be disturbed only in a minute degree by the magnetizing effects of such currents, is a task requiring much care and a great amount of material. Even if this difficult problem were solved, the constant voltage would be at the brushes of the machine and not at the load, where it is needed.

An easy way out of these difficulties is found by considering an important property of the series-wound machine just mentioned, *i. e.*, the rise of E. M. F. as the load on the external circuit rises. If now one takes a good shunt-wound dynamo and adds to the field magnets a few *series* turns wound in the same direction as the shunt, the result is as follows: At no load, the voltage at the brushes is that due to the shunt alone. As the load comes on this voltage would naturally fall off by the loss of voltage from armature resistance and reaction. The series turns, however, at this juncture strengthen the field and thus compensate for these losses. This is the *compound winding* now very generally used. It is shown in diagram in Fig. 30. Ordinarily the series turns are more than would be needed for merely compensating the losses due to armature resistance and reaction, so that the voltage at the brushes under load will rise enough to make up for the increased loss in the line due to carrying heavier current.

Machines thus *over-compounded* five or ten per cent. are in very common use.

The foregoing gives the rudiments of the machines used for generating direct current. It now remains, before taking up the question of power transmission proper, to consider briefly the use of such machines as motors. The underlying principle has been already discussed. The power of a motor to do work depends on the stress of the magnetic field on conductors carrying current in it and free to move. This stress is virtually the same as that which has to be overcome in using the machine as a generator, and reaches a very considerable amount in machines of any size.

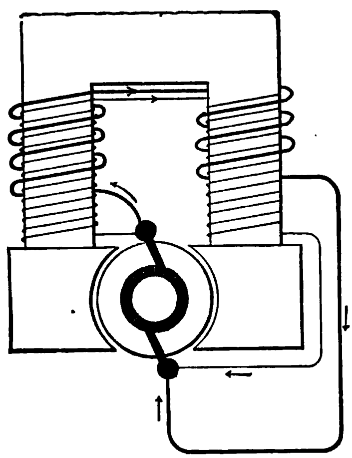


FIG. 30.

In motors with the field strengths often used, the actual drag between the field and the armature wires may amount at a rough approximation to nearly an ounce pull on each foot of conductor in the field for every ampere flowing through the wire. With a 20 HP motor the actual twisting effort or *torque* at the surface of the armature might easily be considerably over a hundred pounds pull. Forces of this size emphasize the need of solid armature construction, with the conductors firmly locked in place, particularly since the magnetic drag is not steady, but comes somewhat violently upon the conductors as they enter the field. With the old smooth core armatures wound with wire, the conductors not infrequently

worked loose and chafed each other, and even the entire winding has been known to slip on the core. In modern windings, either iron clad or modified smooth core, such accidents are nearly impossible.

When the armature conductors of the motor cut through its field as the armature revolves, an electromotive force is necessarily generated in them as in every other case when the magnetic forces on a conductor change. There is thus produced, as a necessary part of the action of every motor, a *counter electromotive force* in the armature. This electromotive force plays a very important part in the internal economy of the motor and is worth looking into.

In the first place, the magnitude of the counter electromotive force determines the amount of current that can flow through the motor when supplied at a given voltage. The resistance of the armature measured from brush to brush may be only a few thousandths or even ten thousandths of an ohm, while the applied voltage may be several hundred volts. The current, however, is not that which would flow through the given resistance under the pressure applied, but the flow is determined by the difference between the applied electromotive force and the counter E. M. F. of the motor, so that in starting a motor when the armature is at rest and there is therefore no counter E. M. F., a resistance must be inserted outside the armature to cut down the initial rush of current.

In the second place, the counter electromotive force measures the output of the motor for any given current. It does this because the very same things, *i. e.*, strength of field, amount of wire under induction, and speed, which determine the output for a given current, also determine the magnitude of the counter electromotive force.

Therefore, when the machine is running as a motor, while the energy supplied to it is the product of the voltage by the amperes which flow through the armature, the output of the motor is determined by the product of the counter electromotive force into the selfsame current; hence, under given conditions, the ratio between the impressed and counter electromotive forces of the motor determines the efficiency of the motor. The difference between these electromotive forces determines the input of energy, since it determines the cur-

rent which may flow; therefore, as the counter electromotive force increases, the efficiency of the motor increases, but the output is limited by the decreased input.

With a fixed electromotive force supplied to the armature, the output of the motor per ampere of current will diminish as the counter electromotive force diminishes, but the total amperes flowing will increase because the difference between the applied and counter E. M. F. has also increased. Thus the total output increases, although at a lower efficiency, when the counter E. M. F. decreases. Since the input (which is determined by the difference between counter and applied E. M. Fs.) multiplied by the efficiency (which is determined by the counter E. M. F.) equals the net output of the motor, this output will be at a maximum when the counter E. M. F. and the effective E. M. F. are equal to each other. This follows from the general law, that the product of two quantities, the sum of which is fixed, will be a maximum when these quantities are equal.

It must be distinctly understood, however, that at this point of theoretical maximum output the motor is very inefficient, and that mechanical considerations prevent the efficiency being wholly determined by the counter E. M. F., while sparking and heating generally prevent working with the counter E. M. F. equal to the effective E. M. F.

In actual practice motors are worked under very diverse conditions, and some of these it is worth while to take up in detail, following the preceding generalizations. The energy may be supplied at constant current, at constant voltage, with neither current nor voltage constant, at fixed or variable speed, and subject to a wide variety of conditions; the motors may be wound either series, shunt, compound, or with various modifications of these windings, and may be either self regulating with respect to various requirements, or regulated by extraneous means. In the ordinary problems dealt with in power transmission, these conditions may be classified in a fairly simple way as follows:

Case I. Series-wound motors at constant current.

Case II. Series-wound motors at constant voltage.

Case III. Series-wound motors with interdependent current and voltage.

Case IV. Shunt-wound motors at constant voltage.

The first class is now comparatively little used, much less than formerly, and hence is not of great practical importance. The second class is very widely used in a particular case, to wit: electric railway practice, and consequently it is of great importance. The third class of motors is used occasionally with great success but not very extensively, while the fourth includes the vast majority of all the machines running for purposes other than electric railway service. These cases, therefore, it is worth while to take up somewhat thoroughly.

CASE I.—Series-wound motors operated with a constant current originally came into use in connection with arc lighting circuits, which for some years formed the most generally available source of current. Such lines are fed from dynamos in which the current is kept constant by special regulation, while the voltage rises and falls in accordance with the load, consisting of lamps or motors in series with each other. We are therefore relieved of any concern about the current, since it is kept constant quite irrespective of what happens in the motor.

Under these circumstances, in a series-wound motor, the torque will be constant, since the field is constant, and the output of the motor will vary directly with the speed. If it be loaded beyond its capacity, it simply refuses to start the load, inasmuch as its torque is limited by the current. If it starts with a load within its limit of torque, its speed will steadily increase until that limit is reached. This may be comparatively soon if the load is a rapidly increasing one, or the machine may race until its own friction of air and bearings, magnetic resistances and the induction of idle currents in the core and frame serve to furnish resistance up to its limit of torque. When running at a given speed, any increase of load causes the speed to fall off, while decrease of load produces racing. Unless these tendencies are controlled, this type of machine becomes almost useless for practical purposes, as regularity of speed under change of load is generally highly desirable. In fact, the tendency to run at constant torque is generally inconvenient. To obviate this very serious difficulty various devices have been tried with tolerable success. The commonest is to vary the torque in accordance with the load

by changing the field strength or by shifting the brushes so as to throw the armature coils out of their normal relation to the magnetic field.

Since the object of such changes is to vary the output at constant current, and since this output is measured by the counter E. M. F. of the motor, the real problem of such regulation is to vary the counter E. M. F. in proportion to the output desired. Therefore the same general means that serve to accomplish this end in an arc dynamo, keeping the current constant and varying the E. M. F., will serve to regulate the corresponding motor.

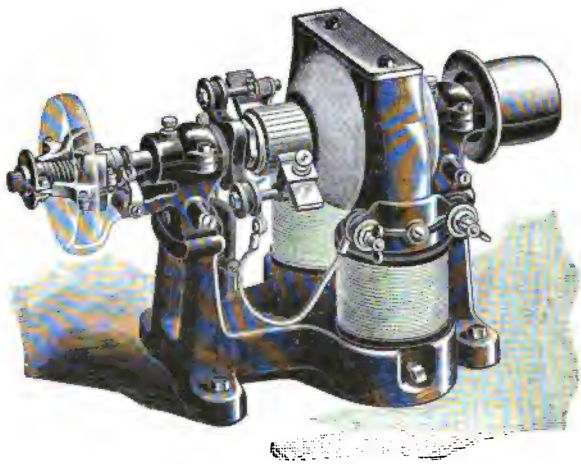


FIG. 31.

As in this case the speed is the thing to be held constant, the usual means taken for working the regulating devices is a centrifugal governor, which generally acts to shift the brushes or to put in circuit more or less of the field winding, which for this purpose is divided into sections. In still other arrangements the governor acts to slide the armature partially into or out of the field, or to work a rheostat which shunts the field magnet, as in the Brush regulator for constant current. An excellent example of a constant current motor regulated on the last mentioned principle is shown in Fig. 31.

As to the operation of these regulating devices, it is tolerably good if everything is carefully looked after and kept in adjust-

ment. The efficiency of such motors is not generally as high as that of other types, especially at light loads, owing to the nearly constant loss in the armature due to constant current working.

In addition, the current is highly dangerous, coming as it does from generators of very high voltage, and even the voltage across the brushes is, in machines of any size, sufficient to give a dangerous or even fatal shock. A 10 HP motor, for example, on the customary 10-ampere circuit, would have a difference of potential of about 800 volts between the brushes at full load. As a few such motors would load even the largest arc dynamos, besides being dangerous in themselves, operations have generally been confined to smaller units. On account of the danger and the mechanical and other difficulties, the arc motor has come to be looked upon as a last resort, is seldom or never used when anything else is available, and, to the credit of the various manufacturers be it said, is nearly always sold and installed with a specific explanation of its general character and the precautions that must be taken with it.

In spite of all these objections, the constant current motor often does good and steady work, and some such motors have been used for years without accident or serious trouble of any kind. They have been employed, however, only sparingly for power transmission work of any kind, and appear to be steadily passing out of use.

Case II.—Series motors worked at constant potential are very widely used for electric railway service and other cases, such as hoisting, in which great variations of both speed and torque are desirable. When supplied at constant potential the speed of a series-wound motor varies widely with the load. In any case the speed increases until the counter E. M. F. rises high enough to cut the current down to the amount necessary to give the torque sufficient for that load and speed.

If the field be strengthened, the motor will give a certain output at a lower speed than before; if it be weakened, at a higher speed; the torque being in these cases correspondingly increased or decreased.

The torque increases rapidly with the current, so that when the counter E. M. F. is small, or zero, as in starting from rest,

the torque is very great, a property of immense value in starting heavy loads. For in starting, not only is the current through the armature large, but the field is at its maximum strength. If the field strength varied directly as the current, the torque would vary nearly as the square of the current.

As a rule, however, these, like most other motors, are worked with a fairly intense magnetization of the fields, so that doubling the magnetizing current by no means doubles the strength of the field. In fact, most series motors for constant potential circuits are of the type used for electric railways and wound so that the field magnets are nearly saturated even with very moderate currents. Hence the torque in such cases increases but a trifle faster than the current. This construction is adopted in order to reduce the amount of iron necessary to secure a given strength of field, and so to lighten and cheapen the motor.

It is quite obvious that while series motors at constant potential have the advantage of being able to give on occasion very great torque, they suffer from the same disadvantage as constant current motors, in that they are not self-regulating for constant speed. A centrifugal governor could, of course, be arranged to do the work, but since it happens that most work requiring great torque also requires variable speed, nothing of the kind is usually necessary.

As previously explained the speed can be easily regulated to a certain extent by changing the field strength, thus changing the counter E. M. F., but owing to the peculiarity of design just noted, this method is rather ineffective, requiring a great change in the field winding for a moderate change in speed.

In general, when a considerable range of speed is needed, constant potential working is abandoned and the speed is changed by varying the impressed E. M. F. by means of a rheostat. If this E. M. F. be lowered, the current decreases and the speed sags off until the new counter E. M. F. is low enough to let pass just enough current to maintain the output at the reduced speed. When the applied E. M. F. is increased the reverse action takes place. Under these circumstances for a fixed load the current is approximately the same independent of the speed; for with a uniform load the torque is constant although the output (*i. e.* rate of driving the load) varies. All

railway motors are regulated in the manner just described, although in addition the field strength is sometimes varied by cutting out or recombining fields. Rheostatic control necessarily wastes energy, and the greatest recent improvement in railway practice consists in reducing the E. M. F. applied to the car motors by throwing the two in series. This secures a low speed economically though the rheostat still comes into play at intermediate speeds.

Speaking broadly then, series-wound motors, while possessing many valuable properties, are limited in their usefulness by their tendency to vary widely in speed when the load

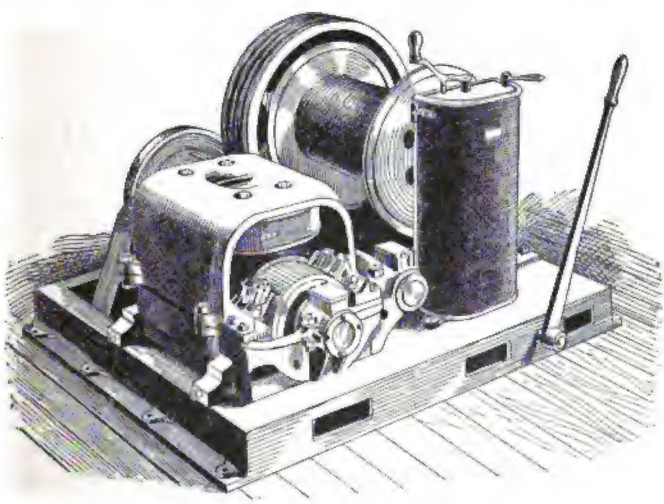


FIG. 32.

changes. Hence they are used chiefly in cases where the speed is to be varied deliberately. A typical motor of this class, such as is used for hoists and the like, with rheostatic control, is shown in Fig. 32.

In spite of the difficulty in regulation, the series motor possesses some considerable advantages: The field coils being of coarse wire are easily and cheaply wound even in motors for very high voltage; the same quick response to changes in current or load that makes it hard to obtain uniform speed is also most important in many kinds of work; the powerful initial torque, coupled with the kindred property of prompt reversal; all these make the series motor pre-eminent for cer-

tain purposes, especially where severe work is to be coupled with hard usage.

There is one case, too, in which the series-wound motor can be made accurately self-regulating for constant speed—a case somewhat peculiar and unusual, but yet worthy of special attention.

CASE III.—We have seen that when the load on a series motor supplied at a certain voltage increases, the speed falls off until the increasing current due to the lessened counter E. M. F. raises the torque sufficiently to meet the new conditions. Imagine now the impressed E. M. F. to be so varied that the slightest increase of current in the motor is met by a rise in the E. M. F. applied to it. Evidently the speed would not have to fall as before, for the greater applied voltage would furnish ample current for all the needs of the load. If the variation in voltage could be made to depend on change of torque, not giving the speed time to change, the regulation would be almost perfect. Such a method has been proposed, but owing to mechanical difficulties has not been used to any extent.

It is possible, however, so to combine a special motor and generator that the former will be very closely uniform in speed quite independent of the load. In this connection we must revert to the properties of the series-wound dynamo. If such a machine be driven at constant speed its electromotive force will increase with the current, since the strength of field, here the only variable factor in the voltage, will increase with the current. If the field magnets of the generator are unsaturated, that is, not so strongly magnetized as to require considerable current to produce a moderate increase of magnetization, they will respond very promptly to an increase of load by raising the voltage. If such a generator be connected to a series-wound motor of proper design, the pair will work together almost as if connected by a belt instead of a long line, and the motor will run at a nearly uniform speed, since the least diminution of speed, with its accompanying increase of current, will be met by a rise in the voltage of the generator. Such an arrangement is shown in diagram in Fig. 33.

In this cut *A* is the generator supplying current to the motor *B*. The machines should be of practically the same

capacity, for the generator cannot supply current except to the one motor without disturbing the regulation. Whenever the load on *B* changes, a very small reduction in speed suffices to raise the voltage of *A* and thereby to hold up the speed of *B*. To this end the field magnets of *B* must be more strongly saturated than those of *A*, else the same increase of current will raise the counter E. M. F. of the motor and defeat the purpose of the combination. If the fields of the two machines are properly designed the generator will increase its voltage under increasing load just enough to hold the motor at speed, as a very slight change in current immediately reacts on the generator.

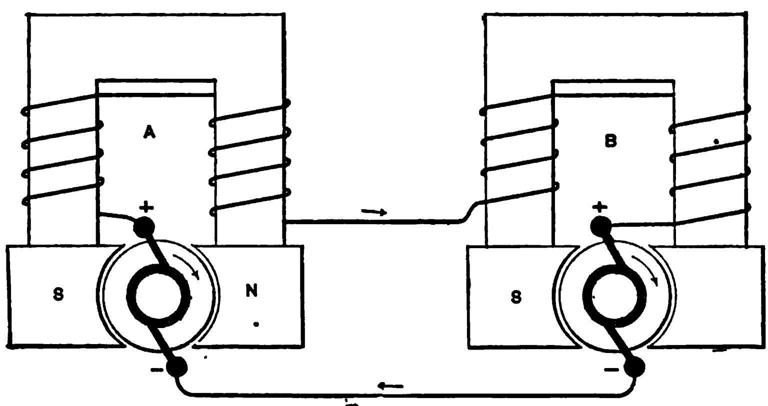


Fig. 33.

It is even possible to make the motor rise in speed under load if the generator is sufficiently sensitive to changes of current. This is generally needless, but it is often useful so to design *A* and *B* that the former will rise in voltage fast enough not only to compensate for the added load on the motor but for the added loss of energy in the line, entailed by the increase of current, thus regulating the motor even at a long distance. It is needless to say that such a system must be so arranged that the generator will take care of everything that tends to change the speed of the motor. When properly adjusted the system is capable of holding the motor speed constant within two per cent. through the range of load for which the machines are planned.

It should be noted in connection with Fig. 33 that, whereas the current circulating in the armature of a generator tends to disturb the magnetic field in one direction in a motor, the same reaction is in the opposite direction. For the current in the motor is driven through the armature against the counter E. M. F., *i. e.* in the direction opposite to that of the current the machine would give if running as a generator. As the effect of the reaction is to skew the direction of the magnetic field that affects the armature conductors, and the commutation must take place when the commuted coil is not under a varying induction, the armature reaction compels one to shift the brushes slightly away from the position they would have if the field were perfectly symmetrical. This shifting is in the direction of armature rotation in a generator, but for the reason above noted has the opposite direction in a motor. In either case it should be only a few degrees.

CASE IV.—Shunt-wound motors are almost invariably worked on constant potential circuits, to which they are particularly well suited. They form by far the largest class of motors in general use and owe this advantage mainly to their beautiful self-regulating properties.

The shunt motor is in construction practically the same as a shunt-wound dynamo. Let us look into the action of such a machine when supplied from a source of constant voltage. If the design be reasonably efficient, the armature will have a very low resistance and the shunt circuit, which includes the field coils, a resistance several hundred times greater. When such a machine is supplied with current of constant voltage at its brushes and is running at any given speed and load, the current through the armature is practically determined by the counter E. M. F. developed, the armature resistance being almost negligible. The shunt is of high resistance and takes a certain small amount of current, determined by the voltage across the brushes. Now let the load increase; the field is, aside from loss of voltage on the line, practically constant, and the first effect of the added load is, as in a series motor, to reduce the speed. But this lowers the counter E. M. F., and consequently the armature current rises and the torque is increased, thereby enabling the motor to operate under the larger load. The torque necessary to enable the motor to

maintain an increased load varies directly as the load and is also directly proportional to the current. But since the current is closely proportional to the difference between the impressed and counter E. M. Fs., it is possible to design a machine so as to run at almost exactly constant speed.

The constancy depends really on the armature resistance, small as it is. For example, a motor is designed to run at 100 volts. Running light the counter E. M. F. is 99.9 volts and with an armature resistance of 0.01 ohm the current will be 10 amperes. The work done is say 1 HP. Now let a full load, say 20 HP, be thrown on. The torque will have to be increased 20 times, requiring 200 amperes. But this will flow through the armature under an effective pressure of 2 volts. Hence the counter E.M.F. will only have to fall to 98 volts to provide current enough to meet the new condition. As the counter E. M. F. varies directly as the speed a fall in speed of less than 2 per cent. will follow the increase of load. This computation neglects all questions of armature reaction as well as the effect of this minute fall in speed on the output, but fairly represents a case that might actually be met with in the best modern practice. In fact, shunt motors have been so designed as to vary no more than 1½ per cent. in speed from no load to full load. A variation of 5 or 6 per cent. is, however, more usual.

When supplied from an over compounded generator so that the impressed voltage may increase with the load, a shunt motor can be operated even more closely to constant speed than indicated above, since there is no longer need for a fall in speed to maintain the requisite difference between the impressed and counter E. M. Fs. In such case any tendency to fall in speed is at once corrected by the rise in voltage on the line. This scheme is seldom used, however, since it is ill fitted for simultaneously operating a number of motors at varying loads, and for single units has no particular advantages over the series-wound pair previously noted, or a very simple arrangement of alternating apparatus.

Not only can the shunt motor be worked at nearly constant speed, but it also has the advantage of permitting a considerable range of speed variation without sacrificing much in the matter of efficiency. We have already seen that a change in

field strength involves a change of speed, since it necessarily alters the counter E. M. F., which in turn modifies the current.

In a shunt motor the immediate effect of a decrease of field strength is to lower the counter E. M. F., letting more current through the armature and increasing the torque. Hence the speed rises until the current and torque adjust themselves to the requirements of the load. On the other hand, if the field be strengthened, the current necessary to carry the load cannot be obtained without a fall in speed. It is clear that the changes of speed thus obtained may be quite considerable, for in a motor such as that just described a variation of 10 per cent. in the field would produce an immense variation of current, which would have to be compensated by a change in speed as great as the change in the field. Inasmuch as these field changes can be produced by varying the field current, which is always small, through a rheostat in the circuit, this change of field strength can be accomplished with but a trifling waste of energy. If the field magnets are comparatively unsaturated, it is not difficult to obtain perhaps 50 per cent. variation in speed. A motor designed for such work is, however, necessarily bulky, as it must be possible to get torque enough to handle the full load with a field much below its normal strength.

It should be noted that even when running at a considerably modified speed, the motor must still be nearly self-regulating for changes in load, for the conditions that govern self-regulation are within moderate limits unaffected by the particular strength of field employed. Only when the armature reaction has been greatly modified will the regulation be sensibly disturbed.

A device sometimes used to improve the regulation of motors essentially shunt wound is the so-called differential winding. This consists of an additional field winding in series with the armature, but around which the current flows in such a direction as to demagnetize the field. The total field strength is then due to the difference between the magnetizing power of the shunt and of this regulating coil. When the load on the motor increases, the additional current due to a minute change of speed will weaken the field and thence cause the motor to run faster until the counter E. M. F. adjusts the current to the

new speed and output. Differential winding obviously requires an extra expenditure of energy in the field, since the shunt and series turns act against each other. It is now used much less than formerly, since it has been found that a well-designed pure-shunt motor will regulate very nearly as well and more efficiently. Fig. 34 shows the Sprague motor wound on this differential plan, now only of historical interest, but which through its good qualities did much to popularize the electric motor in America.

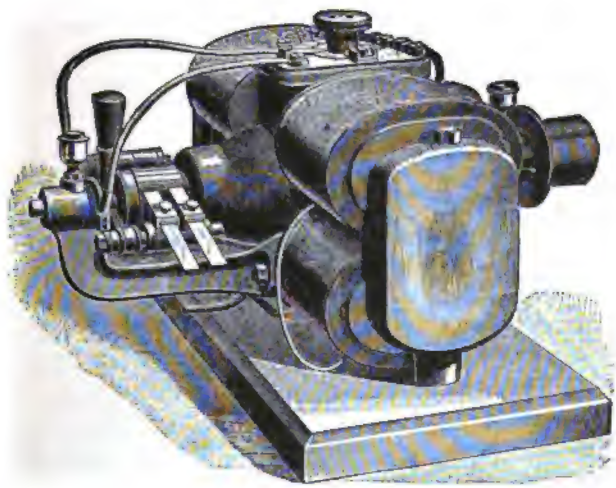


FIG. 34.

Various modifications of shunt- and series-wound motors have from time to time appeared devised for particular adaptation to special purposes or sometimes merely for the sake of novelty. None of them, however, are of sufficiently general importance to find a place here.

POWER TRANSMISSION AT CONSTANT CURRENT.

In its general aspect this method must now be regarded as a makeshift. It came into existence at a time when the only circuits extensively installed were those for arc lighting, and hence, if motors were to be used at all, they must needs be of the constant current type. As incandescent lighting became

more common the arc motors were gradually replaced by shunt motors worked at constant potential. A few constant current plants, especially for motor service, have been installed both here and abroad, but for the most part they have merely dragged out a precarious existence, and are probably doomed to ultimate abandonment.

There is good reason for this. The motors at best regulate indifferently, and there is serious objection to running high voltage wires into buildings when it can be avoided.

The objections of the insurance companies alone are quite sufficient to discourage the practice. The constant current has often been advocated for long distance transmission of power where high voltage is a necessity. For such service the method has the great advantage that the motors do not need extraordinary insulation except from the ground. A constant potential service at 5,000 volts continuous current would be utterly impracticable, if distribution of power in moderate units were to be attempted, while with constant currents it is entirely feasible, although objectionable on the grounds mentioned. In addition, unless a proposed transmission be for power alone, the constant current method shares with constant potential of high voltage the very grave difficulty that an incandescent lamp service is out of the question, without secondary transformation of the necessarily high line voltage to a very moderate pressure. This is difficult and costly with continuous currents of any kind, and doubly so when the troublesome question of regulation at constant current is involved.

To reduce the energy sent over a high voltage continuous current line to a pressure at which incandescent lamps can be fed, two methods are possible. We may pass by the plan of using many lamps in series as of very limited applicability and forbidden by the fire underwriters. First, the required power may be received by a motor of appropriate size, which is belted or coupled to a low voltage generator. This device does the work, indeed, but it involves installing three times the capacity of the lamps desired in machinery of a somewhat costly character, and losing in the motor and generator 15 or 20 per cent. of the energy supplied from the line. The other alternative is to employ a composite

machine combining the functions of motor and generator. This piece of apparatus is variously known as a motor generator, dynamotor, or continuous current converter. It is a dynamo electric machine having a double-wound armature and two commutators. One winding with its commutator receives the high line voltage and operates as a motor. The other winding and its commutator furnishes, as a dynamo, low tension current. The field is common to both windings. Fig. 35 shows a small machine of this kind, adapted to receive 5,000 volts from the line, and to deliver 110 volts, or *vice versa*.

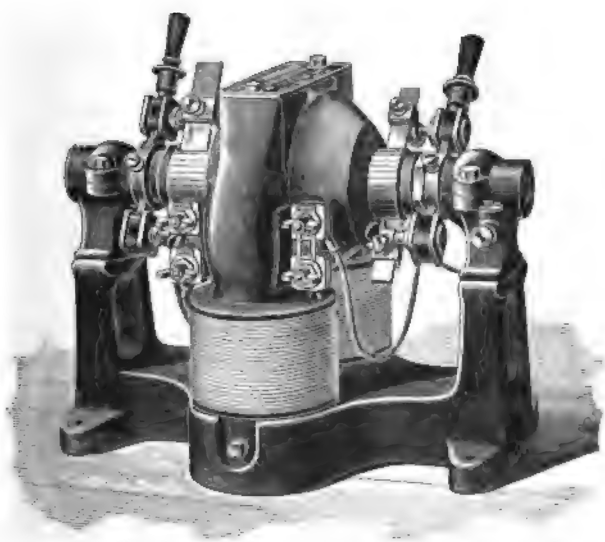


FIG. 35.

This particular machine works at constant voltage on both circuits. Either circuit, however, could be made to work at constant current, provided the means of regulation for this purpose were so chosen as to leave the field and speed unchanged.

The cost of a motor generator, while less than that of two separate machines, is still high, and although its efficiency is somewhat greater than that of the pair mentioned above, it is obtained at the cost of a rather complicated armature, which, from a practical standpoint, is quite objectionable.

In spite of the difficulties incident to working incandescent lamps from a high voltage constant current circuit, the ease with which such circuits can be worked, even if for power alone, at voltages far above those available on the constant potential system, encouraged their installation during the period between the first efforts at long distance transmission and the very recent date at which alternating current apparatus has become thoroughly available. For some years it was constant current or nothing, so far as long distance transmission, coupled with distribution, was concerned.

As a result of the various adverse conditions mentioned, transmission at constant current has never made really any headway in American practice and at present the method is followed to a noticeable extent in only one locality—San Francisco. There, through the activity of local exploiters, constant current power circuits have been established and have been in fairly successful operation for several years.

There have been until recently three companies operating constant current circuits in San Francisco for the distribution of power. The currents employed were of 10, 15 and 20 amperes. Most of the motors are small, a very large proportion of them being under one horse power. The total number of motors in circuit on the various systems was between six and seven hundred. One of the companies is now gradually shifting its motor load on to a 220 volt circuit and abandoning the series distribution; another is planning for a 500 volt power circuit constant potential, to replace its existing system; while the third, which operates by far the largest number of motors, on a 10 ampere circuit, still adheres to its original method, but is getting ready to follow the example of the others.

Except in San Francisco, what few constant current motors are in operation are nearly all on regular arc circuits. Their use is, as a rule, discouraged by the operating companies, and very few new motors are being manufactured or sold; in fact, constant current distribution in modern American practice is almost non-existent and probably will soon pass entirely out of use. Abroad, the conditions are somewhat different, and on the Continent constant current distribution for long distance transmission work has been exploited to a very considerable extent, probably owing to the early and successful

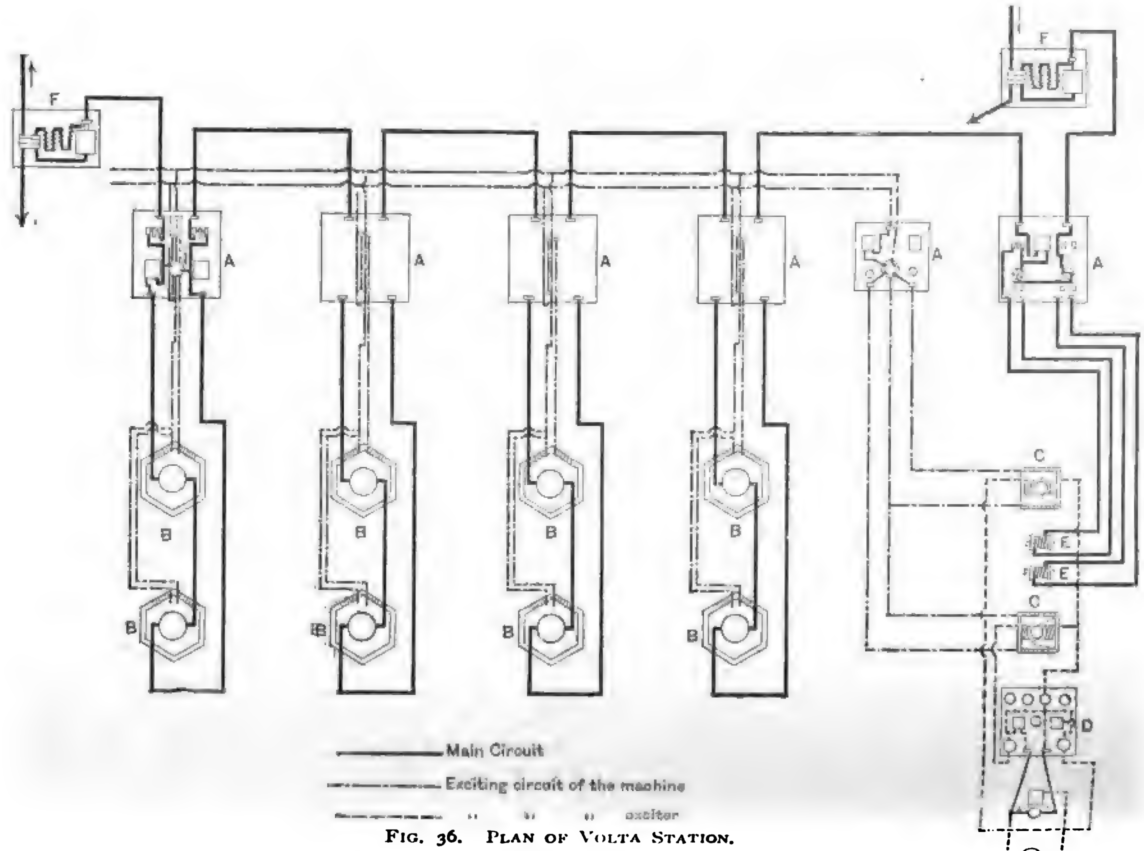


FIG. 36. PLAN OF VOLTA STATION.

establishment of a number of transmission plants for single motors worked on the series system. There are several successful plants operated at constant current, the most considerable of them being that at Genoa, which is by far the best example of the kind and as such is worth more that a passing mention, even although the probability is that it will seldom be duplicated elsewhere.

The Genoa transmission is derived from the River Gorzente, which about fifteen years ago was developed for hydraulic purposes, artificial lakes being established and a tunnel about 1¼ miles long being built for an outlet. Beyond the tunnel, an aqueduct some fifteen miles in length conveyed the water to Genoa, where a considerable amount of power is utilized directly. In this development there was left at the mouth of the tunnel an unused fall of nearly 1,200 feet aside from the head employed in the aqueduct. This has been developed electrically. It was divided into three partial falls of 338, 357 and 488 feet, respectively. At each of these was erected a generating station with its own transmission line. These stations were named after the three renowned electricians, Galvani, Volta and Pacinotti. The first mentioned station was the first installed. It consists of two generators operated in series. Each is of about 50 KW capacity, giving 47 amperes with a maximum pressure of 1,100 volts. Current is kept constant by regulating by hand the speed of the dynamos, through the gate which controls the turbines. Each dynamo is provided with an automatic switch, short circuiting the machine in case of extreme rise in voltage. This Galvani station was a preliminary or experimental station and was followed up by the establishment of two others which supply the power to Genoa. One of these stations, which is thoroughly typical of the system employed, is shown in Fig. 36. It consists of four turbines, each driving a pair of dynamos of a little less than 50 KW output at 45 amperes and about 1,000 volts.

These dynamos are similar to those in the Galvani station, but the regulation for constant current is obtained in a different manner. The dynamos are separately excited, the fields being supplied in parallel from a small dynamo driven by a separate waterwheel. The speed of this exciter is automatically varied by controlling its turbine in response to

changes of current in the circuit. All the dynamos are operated in series, and like those in the Galvani station are direct coupled in pairs. The machines are insulated with enormous care, heavy layers of mica being placed between the magnets and the bed plates, while the windings themselves are very elaborately protected. Carbon brushes are employed, and the commutators are reported to behave admirably. Each dynamo is protected by most elaborate safety devices, as in the Galvani station. The regulation is said to be excellent, even under considerable changes of load.

The third station, Pacinotti, contains eight machines of the same capacity as those in the preceding. They are governed as in the Galvani station by controlling their speed. This, however, is done by an electrical motor-governor controlled by a relay on the main line and working in one direction or the other as the occasion may require. In all the stations are carried out the same thorough precautions regarding insulation, and each machine has around it an insulated floor supported on porcelain. The line voltage from each of the two stations last mentioned is from 6,000 to 8,000, and two circuits are carried into Genoa, the extreme distance of transmission being about eighteen miles. The conductors are for the most part bare, except when passing through villages, and are supported on oil insulators carried by wooden poles, save in some few cases where iron poles have been used. The two circuits running into Genoa transmit power for motors only. As might well be imagined, incandescent lighting would involve some very troublesome transformations.

At full load, nearly 1,000 HP is transmitted over the lines, the motors being of all sizes between 3 and 60 horse power. They are of the ordinary series-wound type, and their speed is automatically controlled by centrifugal governors, which act by varying the field strength. They are provided with carbon brushes, and are reported to operate very successfully.

It is to be noted, however, that the motors are placed in special rooms with insulated floors and walls owing to the enormous voltage which has to be taken into the buildings. They are fitted with heavy fly-wheels to assist the governors, and with automatic switches to short circuit around the motor in case of excessive voltage. The motors are under the

special care of skilled assistants connected with the staff of the generating station, who inspect the lines and go over the motors at intervals of a few days. These extraordinary precautions both in the matter of insulation and skilled attendance account in great measure for the success of what, under American conditions, would have almost infallibly resulted in disastrous failure. The efficiency of the plant from turbine shaft to motor pulleys is said to be a little over 70 per cent.

As may be judged from this description, the whole installation is of enormously complicated character, and the most remarkable thing about it is not so much that it works passably well, as that it works at all. The plan of the Volta station for the most part explains itself. The switchboards for each machine with their plugs for connecting the pair of dynamos coupled to it are shown at *A*, dynamos at *B*, the exciters at *C*, exciter switchboard and rheostat at *D* and the solenoids, which control the exciter turbines, at *E*. Lightning arresters are shown at *F*. These consist of a spark gap, impedance coils in series with the line and condenser shunted around them. Every motor is provided with a similar lightning arrester. Taken all together, this Genoa plant is an excellent example of the constant current system followed to its legitimate conclusion. A description of the system is a sufficiently condemnatory criticism judged from our present point of view; at the same time, it should be remembered that several years ago, while this station was being built, the method adopted was practically the only one available in the existing state of the art. Encouraged, however, by the results obtained at Genoa a similar station has recently been built delivering a maximum of 700 HP at Brescia at an extreme full-load pressure of about 15,000 volts over a 12-mile line.

POWER TRANSMISSION AT CONSTANT POTENTIAL.

The transmission of power to series-wound motors at constant potential is a branch of the art which as regards stationary motors has been developed only in special cases. It is, however, the method universally employed for electric railway work. One or two sporadic efforts have been made to operate electric railway systems at constant current, but with

such indifferent success that the method has been abandoned. Counting in electric railways, it is safe to say that at present the majority of all electrical power transmission in the world is done with series motors worked at constant potential or as nearly constant potential as may be practicable. As before mentioned, regulation is generally obtained through the use of rheostats in series with the motors, thereby cutting down the applied voltage, or by throwing the motors either in parallel or in series with each other, or in the third place by a combination of the above methods. Concerning the operation of motors thus arranged, sufficient has been said to explain the situation clearly. The general good properties of the method are most prominently exhibited in the simplicity of the motor windings and the very powerful effort which can be obtained in starting the motors from rest. These properties are of extreme value in railway service.

Aside from the operation of electric railways, series motors at constant potential are frequently employed for hoists and similar work where a powerful starting torque and considerable range of speed at the will of the operator are desirable. In spite of the large use of motors for such purposes there are no plants either here or abroad which may be said to be operated exclusively after this method, for it is generally found desirable to combine in the same system series-wound motors for severe work and shunt-wound motors for purposes where uniform speed is of prime importance. As a rule the power transmission so accomplished is over a comparatively small distance and really involves the problem of distribution more than transmission alone. A very large number of electric hoists designed by different makers are in use at various points throughout this and other countries, doing service in mines, operating elevators of one kind or another, working derricks and traveling cranes and employed for a large variety of similar purposes. Many of the motors employed are of the railway type.

The voltage utilized for this work in America at least is usually either 200 to 250 volts or 500 to 600 volts, the former being most generally used in mines, where difficulties of insulation are considerable, or in operating motors supplied by three-wire systems already installed. The latter voltage is generally selected for work above ground. None of the plants so

equipped are, however, sufficiently large or characteristic to be worth a detailed description. The power installation and the method of distribution are in general closely similar to those employed for electric railway work. Plants of higher voltage than from 500 to 600 are so infrequent as to be hardly worth considering in practical engineering. It is perfectly possible to wind series motors for voltages considerably exceeding this figure, say for 1,000 or 1,200 volts, or, in rare cases, more, provided the units are of tolerable size, but inasmuch as most plants for the distribution of power require both large and small motors, wound both series and shunt, the general voltage is in nearly every case kept at a point at which it will be easy to meet these varied requirements; therefore 500 volts, the American standard for railway practice, has usually been selected.

The only noteworthy exception may be found in the use of the Edison three-wire system for distribution of power to railway and other motors. By this method it becomes possible to transmit the power at the virtual voltage of 1,000 and to employ 1,000 volt motors, either series- or shunt-wound, for the larger units in order to help in preserving the general balance, while at the same time using motors of all sizes with any kind of direct current winding, connected between the middle wire and either of the outside wires. The advantages of such an arrangement are very evident, and if the number of motors be considerable, so that it is possible to balance the system with a fair degree of accuracy, we have at our disposal a very convenient method for the distribution of continuous currents. It is interesting to note that this scheme found its first considerable development in electric railway service itself. Of course the use of both 110 and 220 volt motors on Edison three-wire systems is very common, but the extension of the plan to operating electric roads, and under conditions which as regards balance are somewhat trying, is a considerable advance in the art of continuous current transmission.

The method of working electric railways on the three-wire system is well shown in Fig. 37. Here the road is a double track one, to which the method is generally best suited. The ground, track and supplementary wires serve as a neutral wire, both tracks being placed in parallel for this purpose

and thoroughly bonded. On a double track road, the cars running on each side of the system will be substantially the same in number, and if the total number of cars be considerable, a very fair balance can be obtained, although never as good as is customarily and necessarily used in an Edison three-wire system for lighting. In order to still further improve the balance of the system and prevent its being disturbed as might otherwise occur by a blockade on one track at some point, it is better to make the trolley wire above each track consist of sections of alternate polarity and of convenient length, so that even in case of a blockade, stopping a considerable number of cars, the load would be removed almost equally from both sides of the system.

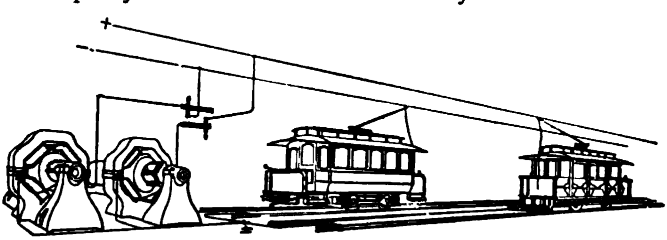


FIG. 37.

Installed in this way, a railway system is operated at a virtual voltage of 1,000, and the saving of copper over the ordinary distribution at 500 volts is considerable in spite of the inevitable lack of balance, and the loss of the track as part of the main conducting system. The total amount of copper required for such a system at 1,000 volts between the outside wires, making a liberal allowance for the neutral wire, which in this case means thorough bonding and supplementary wires for the tracks, is not much in excess of 60 per cent. of the copper required in an ordinary railway system at 500 volts. The advantage, especially in the case of long lines, is obviously worth obtaining.

The three-wire method is not confined to double track roads, as even where only a single track is employed various sections or branches of it may be linked together to form a three-wire system. It is interesting to note that this plan has been in use in several American street railway plants during the past few years, notably at Bangor, Me., and at Portland,

Ore., at both of which places power is transmitted over long feeders from generating stations operated by water power. Very recently, the serious trouble which has been caused on many large electric railway systems by the electrolytic action of the current on gas and water pipes has brought the three-wire system into prominence, all questions of transmission aside. It is obvious that where the earth and rail are used only as a neutral wire, the stray currents are comparatively small, while in an ordinary grounded system the earth and rail return has to take care of the entire current used, and the almost inevitable result is electrolytic action of more or less severity on cables and pipes running in the vicinity of the tracks. Apart from such railway service, the three-wire distribution has been very little used for power transmission purposes either here or abroad, but no particular difficulties are involved and it occasionally may prove a very serviceable method for the distribution of power over moderate distances.

INTERDEPENDENT DYNAMOS AND MOTORS.

Aside from the distribution of power for railway purposes, by far the most interesting kind of power transmission by continuous currents is that in which a special combination of two series machines is employed, giving a self-regulating system comprising a motor unit and a generator unit. This plan has been widely and successfully used abroad, but has not been employed in American engineering practice except in an experimental and tentative way, owing largely to the difficulties that have been encountered in the production of large direct-current generators for high voltage.

While it is not at all a difficult matter to build a machine giving five or six thousand volts with a rather small current, such as is used in arc lighting, the troubles at the commutator have proved forbidding when any attempt has been made to use currents large enough to obtain units of any considerable size. The whole subject of power transmission has been but recently taken up seriously in this country, all the energy of the electrical art being concentrated in lighting and railway work, and so far as the development has now taken place, it has been almost wholly in the line of alternat-

ing current work. It is quite obvious that a system of power transmission such as we are considering possesses very great convenience where single units are to be operated over relatively long distances. In the first place, the inductive difficulties familiar with alternating currents are avoided. In the second place the motors are self-starting under load, a condition that has not been true of alternating machinery until the introduction of the polyphase system. Through the energy of several foreign engineers, notably Mr. C. E. L. Brown, much was done in power transmission by this method long before alternating current apparatus had been suitably developed. The same difficulties were encountered abroad as here. It proved to be very difficult to build machines of sufficient voltage and of any considerable output.

In this connection it is noteworthy that nearly all the plants of this character on the Continent have been installed at relatively low voltages, most of them less than 1,000, corresponding in general character to the American plants over similar distances worked at constant potential. In the very few instances where long distances have been attempted, the usual method has been to employ generators and motors permanently connected together in series, on account of the impracticability of getting sufficient power in one unit at a very high voltage. This proceeding somewhat complicates the system. In addition, the generators and motors have to be especially designed for each other in order to secure regulation; which, of itself, is a considerable disadvantage.

This last difficulty may be in part avoided by using a shunt around the field coils of the generator, thereby changing its regulation under variations of current. A similar device is widely used in this country in connection with compound-wound generators, where a shunt applied across the terminals of the series coils is used to regulate the compounding. In either case, the obvious result of such a shunt is to diminish the change in the field produced by a given increase in current. In this way the necessity for special machines can be partially obviated. The plants installed on this peculiar series plan have been uniformly successful, and permit of the convenient transmission of moderate amounts of power over considerable distances. Such plants have even been employed

in connection with motor-generators to supply a general distribution system, though evidently at a high cost for apparatus.

In order to distribute low tension currents from such a transmission system, it is necessary to employ either a motor, coupled to a dynamo, or a composite machine with a double winding, combining both functions. Either alternative involves the loss of energy substantially equivalent to that lost in two dynamo-electric machines of the capacities concerned. These losses are necessarily much more serious than those in an alternating current transformer. They are likely to amount to from 15 to 20 per cent., so that quite aside from the efficiency of the generating dynamo and of the line, the price paid for the privilege of obtaining a low tension current amounts to nearly a fifth of the total energy transmitted. This is not only enormously greater than the loss in a transformer, but at least double that involved in obtaining a low tension direct current from an alternating current.

For the delivery of power alone, where motors in series coupled to appropriate generators can be used, the method is well fitted for use under certain circumstances, and is closely approximate in efficiency to that which would be obtained by an alternating current transmission over the same distance. It is interesting to know that one of the longest lines over which electrical power to any considerable amount is transmitted is operated on this series direct current system. Many longer alternating transmissions are under construction, but only a few are yet in operation. .

The plant in question is that which is used in operating the Biberest Paper Mills, near Soluere, Switzerland. The power is derived from the River Suze, near Bienne, and the distance of transmission is a little less than twenty miles. At the generating station the available head of water is about forty-five feet, and the quantity is sufficient to generate about 400 HP. The power station contains a 400-HP turbine running at 120 revs. per minute, of which the vertical shaft is connected by means of beveled gear to two 130-KW dynamos. They are six pole machines, Gramme wound, and give at 275 revs. per minute about 40 amperes at 3,300 volts. The two machines are connected in series, giving a working potential of 6,600

volts on the line. It should be noted that great care is taken in insulating them, the bed plates being carried on porcelain insulators. Carbon brushes are employed. The line is a bare copper wire, 7 millimetres in diameter, about No. 1 B. & S. gauge. The line runs through a mountainous country, and is liberally provided with lightning arresters at various points.

The two motors at the mills are duplicates of the generators, the only modifications being those to insure their self-regulation. They run at 200 revs. per minute on 6,000 volts

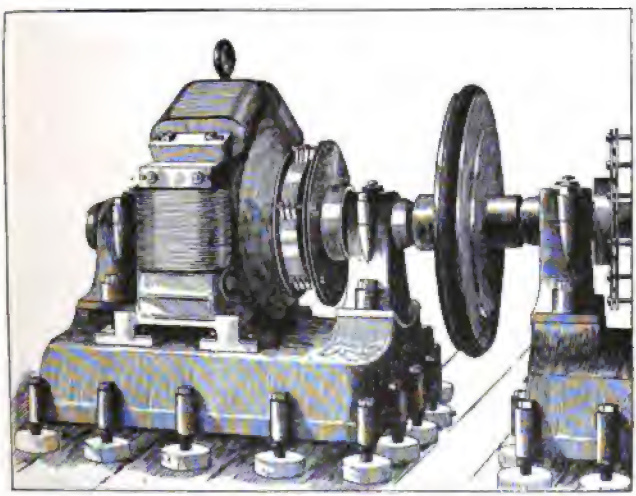


FIG. 38.

delivered, and give about 155 HP each. The commercial efficiency of this interesting system is somewhat in excess of 75 per cent. at full load. Fig. 38 shows one of the motors on its foundation, and its coupling to its mate. This plant is the most striking example of long distance transmission by series-wound generators and motors, and probably exhibits the system at its best.

In this country the above system has not been used in anything more than an experimental way, owing principally to two reasons: first, for moderate distances, involving not more than 1,000 to 1,500 volts, shunt-wound generators and motors working on either the two-wire or three-wire systems

afford better opportunity for distribution, inasmuch as their use is not limited to single mechanical units; second, no serious demand for long distance transmission arose in America prior to the development of the alternating system to the point at which alternating motors became thoroughly practicable. It has been characteristic of American electrical engineering that it has occupied itself with one thing at a time. The development of the electric light was followed by a concentration of energy on the electric railroad, and this has only recently been succeeded by extensive power transmission enterprises, often in themselves involving railway work. Such a mental habit is not conducive to an even development, but probably accomplishes quite as much as a more symmetrical advance.

CONSTANT POTENTIAL SYSTEMS.

Shunt- or compound-wound generators used in connection with shunt-wound motors have found very extensive use in this country in transmissions over moderate distances. The very obvious advantage of such a system is that it permits the ready distribution of power as well as its easy transmission. If it becomes necessary to transmit power from one point to another, the chances are much more than even that at the distributing end of the line it will be desirable to utilize the power in a number of units of varying size. Such an arrangement bars out transmission from series dynamos as a practical method on account of the difficulties of regulation, whereas with shunt-wound apparatus the problem is easy. It often happens, as previously mentioned, that at the receiving end both series and shunt motors are used, the former for hoisting and similar work, the latter for operation at constant speed.

The growth of the electric railway has encouraged the establishment of such transmission plants, and their number is very considerable, scattered over all parts of the Union, not a few of them being in the mining regions of the Rocky Mountains and on the Pacific coast, as well as in various isolated plants through the rest of the country. In most of them, the distances being moderate, an initial voltage of from 500 to 600 has been employed; more rarely, voltages ranging from 1,000

to 1,800. Such plants have been uniformly successful and have done sterling service for some years past. The efficiency of this method of transmission is about the same as that of the series method, just described, but with the advantage that the shunt motor supplied at constant potential can advantageously be distributed wherever the work is to be done, while with series units any distribution of power has to be accomplished by means of shafting and belting or its equivalent.

The net efficiency from generator to driven machine is likely to be rather better with the transmission at constant potential. The generators and motors are of nearly the same efficiency; the line at ordinary distances is customarily worked at about the same pressure in both methods, but distribution by shafting is far less efficient at any but short distances than distribution of electric power by wire. The loss from the centre of distribution to individual motors will very seldom exceed 5 per cent., while the loss in equivalent shafting will seldom be less than 10 per cent., and more often 15 or more; in fact, it generally turns out upon investigation that so far as efficiency is concerned there is a noticeable saving in transmitting power electrically, even within the limits of a mill or large factory, over the result which can be obtained by the use of transmission by shafts and belts. In a large building where the power is to be widely distributed, it seldom happens that the loss in the shafting is less than 25 per cent. Anything in excess of this figure represents remarkably good practice. With motors, 80 per cent. efficiency, if the units are of tolerable size, can be reached without much difficulty, and there are comparatively few cases where the efficiency need fall lower than 75. In such a plant, recently installed in a Belgian gun factory, and described in the last chapter, the guaranteed efficiency was 76.6 per cent. As the efficiency of the dynamo was reckoned at but 90 per cent., the total efficiency would in practice be raised without difficulty to 78 or 79 per cent. at full load.

As regards efficiency in general, aside from the disadvantages previously mentioned in changing the voltage of direct current circuits, the efficiency of transmission by such currents is in itself as high as has ever been reached by other means. There is no material difference between the efficiency of direct and alternating current generators, nor between the efficiency

of direct current motors and the polyphase motors, at least, among alternating motors. In these particulars, the direct current is able to hold its own against all comers.

As regards transmission of power over considerable distances, a case has already been mentioned in which the result is as good as can reasonably be expected. Direct current, however, continually runs into the limitation of available voltage as soon as distribution is to be attempted. Where single motor units are to be used, consisting of either single machines or groups operated as a unit, the efficiency of the system is likely to be as high as that obtained from units of similar magnitude on alternating current systems. The only disadvantage of the direct current in point of efficiency in this particular case is that if the amount of power to be transmitted be large, it is necessary to use generators and motors coupled in series, while if alternating currents were used, one would have the advantage of employing a single machine of equivalent capacity. The principal disadvantage of direct current machinery is the commutator, which at high voltages is sooner or later the source of considerable trouble. Careful mechanical and electrical construction may materially reduce this difficulty, but it always remains to be faced, and is liable at any time to become troublesome.

On long lines, the direct current has the advantage of producing no inductance in the line, an advantage, however, which does not apply to plants of voltage such as would be ordinarily used on long lines, and which, therefore, can advantageously be operated only as single units. Such a single unit system, arranged for alternating currents, can have the inductance of the circuit completely nullified by the simple expedient of strengthening the field of the motor.

Only in plants of moderate voltage, involving distribution of power, does this property of avoiding inductance become of much value, and we shall see later that even here the advantage is more nominal than real, on account of the trifling inductance found in properly designed alternating lines up to a distance at which direct current distribution would become inadvisable on account of limited voltage. In cases of distribution, direct current voltages of over 1,000 are nearly impracticable on account of the difficulty of winding motors

of moderate size for more than this voltage. If the number of units be considerable, the three-wire system affords some relief in this particular. When, therefore, distances of several miles are to be covered and power is to be distributed, direct current is at a disadvantage by reason of the available voltage, which compels a considerable lowering of the efficiency of the system, or a very great increase in the amount of copper.

It must be remembered, however, that in several particulars continuous current has peculiar advantages. In the first place, it is well known that a direct current is decidedly less dangerous than an alternating current of the same nominal voltage, so far as the question of life is concerned. The difference between the two is even greater than would be indicated by the difference in maximum voltage.

An alternating current has a maximum voltage of approximately 1.4 times its mean effective voltage, and in addition to this an alternating current is certainly intrinsically more dangerous by reason of the greater shock to the nervous system produced by the alternations of E. M. F. The ease of transforming alternating current to a lower voltage partially obviates this objection, but the fact remains. So far as danger of fire is concerned, the continuous current has the power of maintaining a much more formidable arc than an alternating current of the same effective voltage; but, on the other hand, the alternating current has somewhat greater maximum voltage with which to start the arc, so that, practically, honors are even.

It is a mistake, however, to suppose that the considerably increased maximum voltage in an alternating current involves greater danger of leakage, or of breaking down insulation under all circumstances. Under many conditions it is highly probable that the electrolytic strain from continuous current on insulating materials, particularly when damp, is more destructive than the added electrostatic strain of an alternating current. Within any voltages now employed, the total difference is probably immaterial. In the matter of one of the great dangers to an overhead line and apparatus, *i. e.*, injury from lightning, direct current has a very material advantage in that it is possible to use coils of considerable self-induction in connection with such circuits, so as to keep

oscillatory discharges, like lightning, out of the machines. This is well shown in the singular freedom of arc lighting stations from serious damages to the machines by lightning, as compared with stations containing other kinds of electrical apparatus. In this case the magnets of the arc machines themselves act as a powerful inductance, tending to throw the lightning to earth. High voltage, shunt-wound dynamos and alternators are much more sensitive in this respect.

Consequently, part of the price one has to pay for the privilege of utilizing alternating currents is extra care with respect to protective devices against lightning. In the present state of the art, the best field for transmission and distribution of power by continuous currents is in cases involving distribution over moderate distances, within, say, a couple of miles from the centre of distribution, and even then in problems where lighting is not an essential part of the work. The voltage of a lighting circuit is determined by the voltage of the lamps which can be employed upon it, and this is so limited that if lighting is to be done on the same circuit as power distribution there are very few cases where such a combined system can be successfully used with continuous currents.

At all long distances continuous current is at a disadvantage in point of available voltage where distribution is to be done, and has no very material advantages for single unit work. Nothing short of a revolution in the art of making commutators can render continuous current thoroughly available for high voltages, and even then only in units of moderate size. In this lies its weakness. Its strength is largely in its present firm foothold in electrical practice, and in the fact that standard apparatus of this kind is available everywhere and is manufactured in large quantities by numerous makers. It is, furthermore, interchangeable to a degree which will never be true of alternating-current machinery until there is far greater unity in alternating-current practice than we are likely to have for some years to come.

CHAPTER IV.

SOME PROPERTIES OF ALTERNATING CIRCUITS.

WE have already seen in Chapter I that the current normally produced by a dynamo-electric machine is an alternating one, so that a continuous current exists in the external circuit only in virtue of the commutator. Until within the last decade the original alternating current was utilized to but a trivial extent. Nevertheless it possesses certain properties so valuable that their practical development has wrought a revolution in applied electricity.

To describe these properties with any degree of completeness would require several volumes the size of the present, and would involve mathematical considerations so abstruse as to be absolutely unintelligible to any save the professional reader. We shall therefore at the very start drop the academic methods of treatment and confine ourselves, so far as possible, to the physical facts concerning those properties of alternating currents which have a direct bearing on the electrical transmission of energy. This discussion will therefore be somewhat unconventional in form, although adhering rigidly to the results of experiment and mathematical theory. The student who is interested in the exact development of this theory will do well to consult the excellent treatises of Fleming, Mascart and Joubert, Bedell and Crehore, and Steinmetz, all of which are full of valuable demonstrations.

The fundamental differences between the behavior of continuous and of alternating currents lie in the fact that in the former case we deal mainly with the phenomena of a flow of electrical energy already steadily established, while in the latter case the phenomena of starting and stopping this flow are of primary importance. These differences are akin to those which exist between keeping a railway train in steady motion over a uniform track, and bringing it up to speed from a state of rest. In steady running the amount of, and the

variations in the power needed, depend almost wholly on the friction of the various parts, while in starting both the power and its variations are profoundly affected by the inertia of the mass, the elasticity of the parts, and other things that cut little figure when the train is up to a uniform speed.

The characteristic properties of alternating currents are due mainly to the starting and stopping conditions, and are only incidentally affected by the circumstance that the flow of current alternates in direction. As, however, this alternating type of current is in general use and its uniform oscillations give the best possible opportunity for observing the effect of repeated stops and starts, we will look into the generation of alternating current, not forgetting that for certain purposes we shall

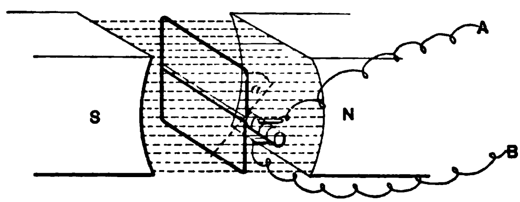


FIG. 39.

have to recur to the phenomena of a single stop or start in the current.

Fig. 39 shows an idealized generator of alternating currents. It is composed of a single loop of wire arranged to turn continuously in the space between the poles of a magnet. This space is a region of intense electromagnetic stress directed from pole to pole, as indicated by the dotted lines. The two ends of the loop are connected to two insulated metallic rings connected by brushes to the terminals A and B of the external circuit. We have already seen that what we call electromotive force appears whenever the electromagnetic stress about a conductor changes in magnitude. Now in turning the loop as shown by the arrow, the electromagnetic stress through it changes, and of course sets up an electromotive force. In the initial position of the loop shown in Fig. 39, it includes evidently the maximum area under stress; after it has turned through an angle a, this area will be much lessened, and when $a = 90°$, the loop will be parallel to the plane of the electromagnetic stress and hence can include none of it at all.

But the resulting electromotive stress is, other things being equal, proportional to the rate at which work is expended in uniformly turning the coil; *i. e.* it is proportional to the *rate of change* in the electromagnetic stress included by the coil. This rate is, during a single revolution, greatest when the sides of the loop are moving directly across the lines of stress, and least when moving nearly parallel to them. Hence we see from Fig. 39 that the electromotive force in our coil will be a maximum when $a = 90°$ or $270°$ and a minimum in the two intermediate positions. For a simple loop it is easy to compute exactly the way in which the electromotive force will vary as the loop turns. The area of strain included by the coil in any

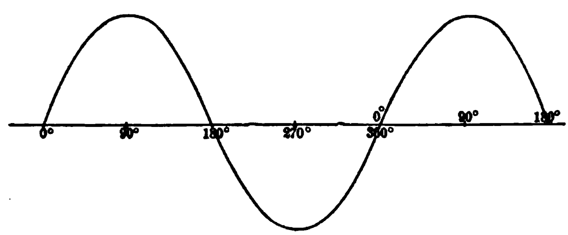


FIG. 40.

position is proportional to the cosine of the angle *a*, hence for uniform motion the rate of change in the area is proportional to the sine of *a*. Therefore the E. M. F. at every point of the revolution is proportional to sine *a*.

If now we draw a horizontal line and measure along it equal distances corresponding to degrees, and then, erecting at each degree a line in length proportional to the sine of that particular angle, join the ends of these perpendiculars, we shall have an exact picture of the way in which the E. M. F. of our loop rises and falls. Fig. 40 is such a curve of E. M. F.—a so-called "sine wave."

This simple form of E. M. F. curve—the "sine wave"—is assumed to exist in most mathematical discussions of alternating current to avoid the frightful complications which would result from assuming such E. M. F. curves as often are found in practice. This assumption is somewhat rash, for a true sine wave is never given by any practical generator, but the error does not often invalidate any of the conclusions, for the exact

form of the wave only matters in discussing certain cases, where it can often be taken into account without much difficulty.

Actual alternating generators give curves of E. M. F. greatly influenced by the existence of an iron armature core which collects the lines of force so that as the core turns the change of stress through the armature coils is not directly proportional to anything in particular. A glance at the rudimentary dynamo of Fig. 8, Chapter I, will suggest the reason. It is evident enough that the armature could turn almost 30° from the horizontal with scarcely any change in the magnetic relations

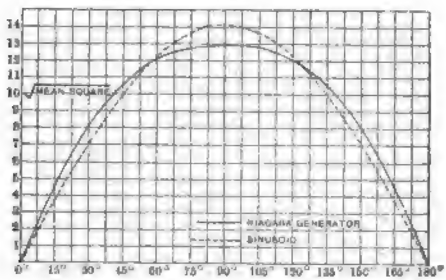


FIG. 41.

of the coils. The result would be a wave with a very flat and depressed top, since the rate of change of induction would be very moderate when it should be considerable. The practical bearings of wave form on power transmission work will be taken up in the next chapter. At present it will suffice to say that the best standard alternators give a fairly close approximation to the sine form. Fig. 41 shows the E. M. F. curve of one of the great Niagara generators. This is an excellent example of modern practice and shows a form slightly flatter than the sine curve and with a mere trace of depression at the crest. Plenty of machines are in operation, however, that give curves not within hailing distance of being sinusoidal—*e. g.* Fig. 42, which shows the E. M. F. curve of one of the earliest alternators designed for electric welding. In this case there is a far sharper wave than the sinusoidal, of a curious toothed form. Many of the early alternators with ironclad armatures gave curves quite far from the sine form, generally rather pointed, while the tendency in recent machines has been rather in the opposite

direction, toward curves like Fig. 41, although seldom so nearly sinusoidal.

An alternating generator gives then a series of waves of E. M. F. alternating in direction, but, from the construction of the machine, of uniform magnitude.

Now as to the current produced by this oscillating electromotive force. In ordinary work with continuous currents, the

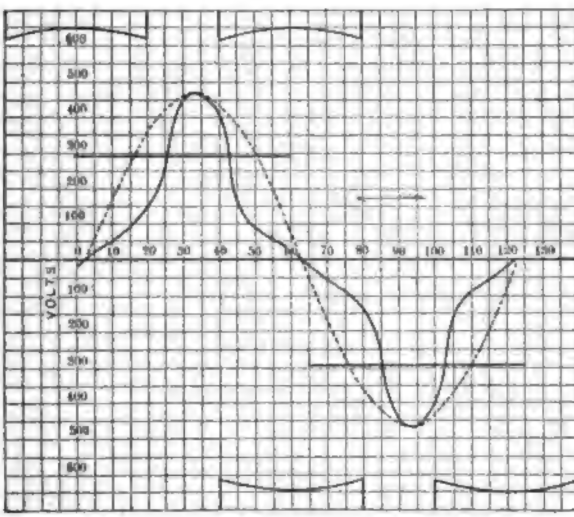


FIG. 42.

current corresponding to each successive value of the E. M. F. would be very easy to determine by simple reference to Ohm's law, $C = \frac{E}{R}$. If the dynamo of Fig. 39 gave one volt maximum E. M. F. and were connected through a simple circuit of one ohm resistance the maximum current would be one ampere, and the current at all points would be directly proportional to the voltage. Hence if the E. M. F. varied as shown in Fig. 40, the current would vary in precisely the same manner and the curve showing its variation would, if drawn to the same scale, exactly coincide with the curve of Fig. 40. This would be generally true if we had only resistance to consider, and the treatment of alternating currents would then be very simple.

But the starting and stopping of current which takes place periodically in alternating circuits produces great changes in the electromagnetic stresses about the conductors, and these changes are in turn capable of very important reactions. They give to the alternating current its most valuable properties, but also involve its action in very curious complications.

Turn back to Chapter I and examine Fig. 4. We see from it that whenever the electromagnetic stresses about a circuit as *A*, change by the variation of the current flowing in it, an E. M. F. is set up in the parallel circuit *B*, opposing the change of E. M. F. in *A*. This fact, as we shall see later, is the root of the alternating-current transformer. Suppose now that in the circuit of our alternator is a coil of wire wound in

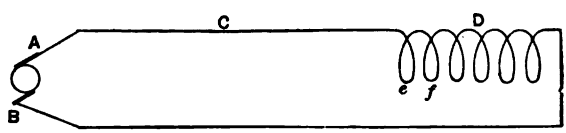


FIG. 43.

close loops as shown in Fig. 43. Here *A* and *B* are the dynamo terminals, *C* the general circuit and *D* the aforesaid coil. Let an E. M. F. be started in the direction *A C D*. The resulting current flows through *D*, but the electromagnetic stresses set up by the current about for instance, the loop *e*, produce an E. M. F. in neighboring coils tending to drive current in a direction opposite to that from the dynamo. In other words *e* acts toward *f* just as *A* acted toward *B* in Fig. 4. Thus each turn tends to oppose the increase of current in the others. When the current in *C* ceases to vary, of course the reactive E. M. Fs. in *e* and *f* stop, for there is for the moment no change of stress to produce them, but as the main current begins to decrease, the reactive E. M. Fs. set in again.

The main or "impressed" E. M. F. is thus opposed in all its changes by the reactive or "inductive" E. M. F. due to the combined action of the loops at *D*. Hence the impressed E. M. F. in driving current through the system has to overcome, not only the resistance of the conductors, but opposing electromotive forces. Therefore since a part of the impressed

E. M. F. is taken up with neutralizing the inductive E. M. F., only the remainder is effective against the true resistance of the circuit. Ohm's law, then, cannot apply to alternating circuits in which there is inductive action, except in so far as we deal with the "effective" E. M. F. The relation between the impressed E. M. F. and the current is not $C = \frac{E}{R}$, but $C = \frac{E}{R}$ less a quantity depending on the amount of inductive E. M. F. encountered.

This state of things leads to two very important results: First, the current in an inductive circuit is less than the impressed E. M. F. would indicate. Second, this current

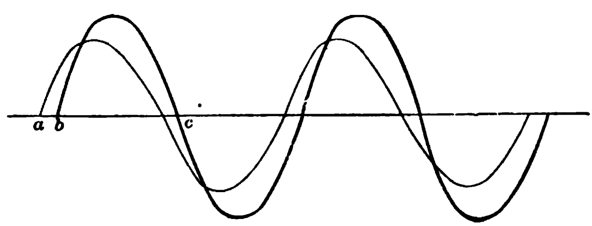


FIG. 44.

reaches its maximum later than the impressed E. M. F. For the current depends on the effective E. M. F., and for each particular value of this the impressed E. M. F. must have had time to rise enough to overcome the corresponding value of the inductive E. M. F. The current is thus damped in amount and caused to lag in "phase" as shown in Fig. 44. The heavy line here shows the variations of the impressed E. M. F. and the light line the corresponding variations of current in a circuit containing inductive reaction—*inductance.* The distance *a b* represents the "angle of lag," while *b c* is 180° as shown in Fig. 39. Very similar relations are found in practice, although the lag is often greater than shown in the cut, particularly when alternating motors are in circuit. Fig. 45 shows the curves of E. M. F. and current from a very small alternating motor at the moment of starting. The angle of lag in this case is a trifle over 45°, and the curves are much closer to sine waves than is usual.

The inductive E. M. F., as has already been explained, is due

to the magnetic changes produced by the variation of the current. Just as in the dynamo of Fig. 39, the actual amount of E. M. F. is directly proportional to the rate of change in magnetic stress, which is in turn proportional to the change of current. The inductive E. M. F. is therefore at every point proportional to the rate of variation of the current. But the current wave is, like the impressed E. M. F. wave, still approximately a sine curve, for it has been merely shifted back through the angle of lag and although damped it has been

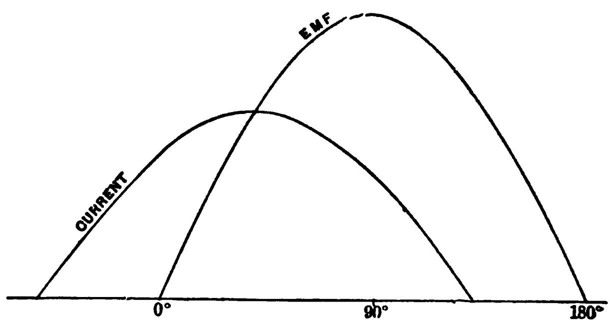


FIG. 45.

simply changed to a different scale. Being still essentially a sine curve its rate of variation is a cosine curve, or what is the same thing a sine curve shifted backward a quarter period, 90°. Indeed this is at once evident, for since the current varies most slowly at its maximum, the inductive E. M. F. must be a minimum at that point, *i. e.* it must be 90° behind the current in phase, while since E. M. F. and current vary symmetrically, in general the forms of the two curves will be similar. The effective E. M. F. which is actually engaged in driving the current is a wave in phase with the current it drives and of similar shape, *i. e.* a sine curve.

We have then in an inductive circuit three E. M. Fs. to be considered:

I. The impressed E. M. F., acting on the circuit.

II. The inductive E. M. F., opposing I.

III. The effective E. M. F., the resultant of I. and II.

Plotting the respective curves, they bear to each other the relation shown in Fig. 46. Here *a* is the impressed E. M. F., *b* the effective E. M. F. (or the current) lagging behind *a*

through an angle usually denoted by φ, and c is the inductive E. M. F. 90° behind b. Now since b is the resultant of the interaction of a and c, and we know that b and c are 90° apart in phase, it is comparatively easy to find the exact relation between the three.

For we can treat electromotive forces acting at known angles with each other just as we would treat any other forces working conjointly. If for example we have a force $A\ B$, Fig. 47, acting simultaneously with a force $B\ C$, at right angles to it, the magnitudes of the forces being proportional to the lengths of the lines, the result is the same as if a single force in magnitude and direction $A\ C$ were working

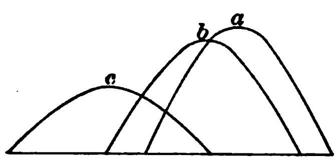


FIG. 46.

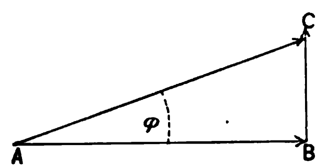


FIG. 47.

instead of the two components. This is a familiar general theorem that proves particularly useful in the case in hand.

If we take $A\ B$ equal to the effective E. M. F. and $B\ C$ equal to the inductive E. M. F., then $A\ C$ is the impressed E. M. F. It at once appears that the angle between $A\ B$ and $A\ C$ is φ, the angle of lag. Then from elementary trigonometry it appears that

$$A\ B = A\ C \cos \varphi$$
$$C\ B = A\ C \sin \varphi = A\ B \tan \varphi, \text{ hence}$$
$$\tan \varphi = \frac{C\,B}{A\,B}.$$

We are therefore in a position to determine the three E. M. Fs. and the angle φ, knowing any two of the four quantities. Thus for a given impressed E. M. F., E, such as is found on any constant-potential alternating circuit, the effective E. M. F. which determines the current is given by $E \cos \varphi$. As φ grows less and less through decrease of the inductive E. M. F., $A\ C$, the impressed E. M. F. necessary for a given current, also decreases, and finally when φ becomes

zero, $A\ C = A\ B$. In other words the impressed E. M. F. is then simply that needed to overcome the ohmic resistance.

For any particular current, then, $A\ B$ is directly proportional to the resistance of the circuit, while $C\ B$ is directly proportional to the "inductance" of the circuit, that property of the particular circuit which determines the inductive E. M. F. Calling this I we may redraw Fig. 47 in a very convenient form—Fig. 48. Here we see the relation between R and I in determining the impressed E. M. F. necessary to drive a certain current through an inductive circuit. The magnitude of the E. M. F. evidently is $\sqrt{R^2 + I^2}$ if the units of measurement are chosen correctly, and it is always proportional to this quantity, which is related to the impressed E. M. F. as resistance is the effective E. M. F.

Hence $\sqrt{R^2 + I^2}$ has sometimes been called "apparent resistance." The more general name, however, is impedance, which indicates the perfectly general relation between E. M. F. and current. If I be zero, as in a continuous-current circuit, then the impedance becomes the simple resistance. We can now write out some of the general relations of current and E. M. F. in alternating circuits as follows, calling E the impressed E. M. F. as before:

$$C = \frac{E}{\sqrt{R^2 + I^2}}$$

$$E = C\sqrt{R^2 + I^2}$$

and with respect to the angle of lag,

$$\sqrt{R^2 + I^2} = \frac{E}{C}$$

$$I = R \tan \varphi$$

$$\tan \varphi = \frac{I}{R}.$$

Hence knowing the angle of lag and the resistance of a circuit the inductance can be found at once. The angle of lag, depending on the ratio of I and R, must be the same for all circuits in which this ratio is the same. Also in

any circuit of given inductance increasing the resistance diminishes the angle of lag, while of course also diminishing the current for a given value of E. In fact since I does not represent work done, for the inductive E. M. F. represents merely a certain amount subtracted from the impressed E. M. F. by the reaction of the circuit, any process which for a given value of E increases the energy actually spent in the circuit is accompanied by a diminution of the angle of lag.

This freedom of the circuit from any energy losses due to I is a fact of the greatest importance. It is fully borne out by experiment and there is besides good physical reason for it. For since current and E. M. F. are the two factors of electrical energy there can be no energy when the product of

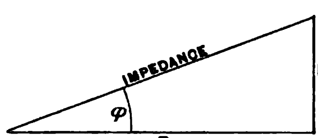


FIG. 48.

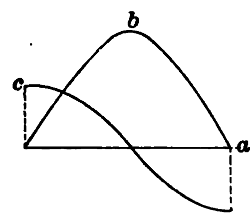


FIG. 49.

these factors is zero. Note now Fig. 49, developed from Fig. 46. Hence a is the line of zero E. M. F. and current, b the current curve for a single alternation, and c the corresponding curve of inductive E. M. F. 90° behind the current. When b is a maximum c is zero and *vice versa*. And since c is equally above and below the zero line during each alternation of current, the average inductive E. M. F. is zero and the average energy throughout the alternation is zero. The same conditions would evidently continue if instead of an alternation we took a complete *cycle* (*i. e.* the whole curve from the time the current starts in a given direction until it starts in the same direction again) or any number of cycles. Thus I must be entirely dropped out of consideration in discussing the question of work done in an alternating circuit. And since E differs from E_1, the effective E. M. F., only by a function of I, the energy value of which is zero, the energy in the circuit is exactly measured by E_1 and the corre-

sponding current which, as we have seen, is in phase with it. But

$$E_1 = E \cos \varphi.$$

Hence multiplying both members of this equation by C to reduce to energy,

$$\text{Energy} = C\,E_1 = C\,E \cos \varphi.$$

That is, the energy in an alternating circuit is equal not to the impressed E. M. F. multiplied by the current but to their product multiplied by the cosine of the angle of lag. The product $C\,E$ is sometimes called the *apparent* energy to distinguish it from $C\,E_1$, the actual energy. This apparent energy is that obtained by measuring the amperes and the impressed volts and taking their product. The real energy is that which would be obtained by putting a wattmeter in circuit. Hence

$$\frac{\text{watts}}{\text{volt-amperes}} = \cos \varphi,$$

a convenient and common method of measuring the angle of lag. If in addition the value of I is wanted it can be obtained at once from the expression for tangent φ already given.

We thus see that the energy in an inductive circuit is not directly proportional to the voltage as measured but to the effective voltage, which is less by an amount depending on the inductance. This difference is sometimes referred to as the "inductive drop" in a circuit. The result is that to drive a given current through an inductive circuit the generator must give a voltage depending on the impedance of the circuit. On the other hand if an inductive circuit be fed from a given impressed E. M. F. the current required to represent a given amount of *energy* exceeds that required in a non-inductive circuit in the ratio of 1 to the cosine of the angle of lag. The net result, then, of inductance in an alternating circuit is to increase the E. M. F. at the generator required to produce a given E. M. F. at the load, and to increase the current required to deliver a given amount of energy.

The E. M. F. and current are here supposed to be measured in the ordinary way, by properly designed voltmeters

and ammeters. In power transmission work inductance in the circuit (line or load or both) means that the dynamo has to give voltage enough to overcome the impedance of the system and still to deliver the proper number of volts at the motor, while the motor will take extra current enough to compensate for the lag between the E. M. F. at its terminals and the resulting current.

The dynamo thus has to be capable of giving a little extra voltage and the motor must be able to stand a little extra current. In other words both machines must have sufficient margin in capacity to take care of this matter of lagging current.

We have already seen the general relation between resistance, inductance, and impedance. Let us now look into the quantity last mentioned so as to see its numerical relation to the others. If a circuit has a certain resistance in ohms and a given inductance, what is its impedance, *i. e.* the ratio between the measured voltage and the measured current?

The real question involved is the value of the inductive E. M. F. This, like any other E. M. F., is proportional to the rate of variation of the electromagnetic stress which produces it. Its total magnitude depends on the rate of variation of the current and the ability of this current to set up stresses which can affect neighboring conductors as in Fig. 43. This latter property depends on the number of turns, their locality with reference to each other, and other similar conditions which depend simply on the physical nature of the circuit and so for any given circuit are settled once for all. These properties are defined on the basis of their net effect, and the *ratio* of the rate of variation of the current to the inductive E. M. F. produced by it in a given circuit is usually known as L, the "coefficient of self induction" of that circuit. The total inductive E. M. F. is then equal to L, multiplied by the actual rate of current variation expressed in such units as will fit the general system by which E, R and other quantities are concordantly measured.

Expressed in this way the rate of current variation in an alternating circuit is $2 \pi n$, where n is the number of *cycles per second*, and π has its ordinary meaning of 3.1416. Hence the inductance of the circuit is numerically $2 \pi n L$, the last factor being dependent on the nature of the circuit and denoting

the inductance per unit rate of current variation. The $2 \pi n$ factor gives the actual rate of current variation, which may change to any amount, while L remains fixed. L therefore may at all times in a given circuit be expressed in terms of any unit that is conveniently related to other electrical units.

Such a unit inductance is the *henry*, which is the inductance corresponding to an inductive E. M. F. of 1 *volt* when the inducing current varies at the rate of 1 *ampere per second.*

If therefore L for any circuit is known in henrys the total inductance I is $6.28\, n\, L$.

We are now ready to apply a numerical value to I in Fig. 48 and the resulting equations.

For example let us suppose that a certain alternating circuit has a resistance of 100 ohms and $L = 0.1$ henry. The im-

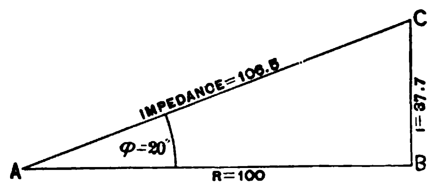


FIG. 50.

pressed E. M. F. is 1,000 volts. What will be the current and its angle of lag? Lay off $A\,B$ Fig. 50, 100 units long. Then at B, to the same scale erect a perpendicular $B\,C$, $2 \pi n L$ in height. If we are dealing with an alternating circuit of 60~ per second, such as is often used for power transmission, $2 \pi n L$ will be 37.7 units high. Now join $A\,C$ and the resulting length on the same scale is the impedance in ohms. But $A\,C = \sqrt{R^2 + I^2} = \sqrt{100^2 + 37.7^2} = 106.9$ nearly. And since the current equals the impressed E. M. F. divided by the impedance, the current in this case would be 9.36 amperes instead of the 10 amperes due if there had been no inductance. And since $\tan \varphi = \frac{I}{R}$ it is here .377, which corresponds to an angle of 20° 40′.

Also, since $E = C \sqrt{R^2 + I^2}$, we can readily find the impressed E. M. F. required to produce in this circuit any given current. For $C = 10$ amperes, $E = 1{,}069$ volts and so on.

We have seen that $\cos \varphi = \dfrac{\text{watts}}{\text{volt-amperes}}$ so that in the

case in hand where $\cos \varphi = .936$ the actual energy in the circuit is 93.6 per cent. of that indicated by the readings of voltmeter and ammeter.

This factor, $\cos \varphi$, connecting the apparent and the real energy, is known as the "power factor" of the circuit.

As $I = R \tan \varphi$, and in any given case n is known, L can readily be obtained from a measurement of lag in a circuit of known resistance. It must be remembered, however, that if the inductance is due to a coil having an iron core, the value of L will change when the magnetization of the iron changes, so that results obtained with a certain current will not hold exactly for other currents. The values of L found in practice cover a very wide range from a few thousandths of a henry in

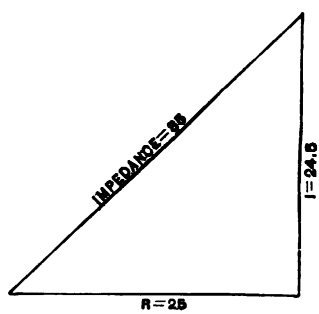


FIG. 51.

a small bit of apparatus like an electric bell, to some hundreds of henrys in the field magnets of a big dynamo. L in fact is nearly as variable as R.

As a practical example in inductance effects we may profitably consider the effect of alternating current in a long circuit. Suppose for example we have a circuit 50,000 ft. long composed of No. 4 B. & S. copper wires. The wires are about 1 ft. apart and about 20 ft. above the ground. What voltage will be required to deliver 10 amperes through this circuit at 130 cycles per second, and what will be the angle of lag? The resistance of this wire is 0.25 ohms per 1,000 ft. L, its coefficient of induction, is .0003 henry per 1,000 ft. The total resistance of the circuit is then 25 ohms and its total inductance, $I, = 6.28 \times 130 \times .03 = 24.5$. Plotting as before these values, in Fig. 51 we have the impedance equal to

$\sqrt{25^2 + 24.5^2} = 35$ ohms. Hence E must be 350 volts instead of the 250 that would suffice in the case of continuous current. Tan $\varphi = \frac{24.5}{25} = .98$. The corresponding angle is 44° 25′. The ratio of impedance to resistance in this case is 1.4 : 1. This ratio, often called the impedance factor, is a very convenient way of treating the matter, and tables giving its value for common cases will be given later. In case of apparatus being connected to the circuit, the computation of its effect is easy. If it has resistance R^1 and inductance I^1 then the total impedance of the circuit will be $\sqrt{(R + R^1)^2 + (I + I^1)^2}$ and so on for any number of resistances and inductances, the impedance being always equal to the square root of the squared sum of the resistances plus the squared sum of the the inductances. Thus an inductance added anywhere in circuit changes the total impedance and the angle of lag.

There are several ways of looking at inductance, according as one wishes to deal more particularly with inductive E. M. F., the changes in electromagnetic stress which produce it, or the energy changes which accompany it. The first point of view is the one here taken, in accordance with the definition of the henry just given. Hence the henry may be called unit inductance, in which case the quantity I which we have been considering measures the inductive E. M. F., and since it is the product of the inductance for unit rate of current change multiplied by $2\ \pi\ n$, (the rate of current change in angular measure), it is sometimes referred to as *inductance-speed.*

In alternating-current working inductance may easily become quite troublesome, through the "inductive drop" in the line and the necessity of sometimes delivering a current quite out of proportion to the energy. Thus in alternating-current lighting plants during the hours of daylight when the actual load is small, the current may be of quite imposing size from the lag produced by the inductance of the unloaded transformers in circuit. The sort of thing which happens may readily be figured out. Suppose we are dealing with a transformer or other inductive apparatus having a resistance of 5 ohms and $L = 1$ henry. The impedance at 60 ~ will then be $\sqrt{5^2 + (6.28 \times 60 \times 1)^2} = \sqrt{25 + 376.8^2} = 377.8$ ohms, substantially the same as the inductance alone, and under an

impressed E. M. F. of 1,000 volts the resulting current would be 2.65 amperes. But $\tan \varphi = \frac{377.8}{5} = 75.56$. Hence $\varphi = 89° \, 15'$ and $\cos \varphi = .013$. Therefore while the apparent energy is $2.65 \times 1{,}000 = 2{,}650$ watts the real energy is only $2{,}650 \times .013$ watts $= 34+$: really the loss due to heating the conductor. This is of course a very exaggerated case, as it takes no account of the energy that would be required to reverse the magnetization in whatever iron core the apparatus might have. It does, however, show very clearly that the current flowing depends practically on the inductance and very little on the resistance, and that the angle of lag is so great that the dis-

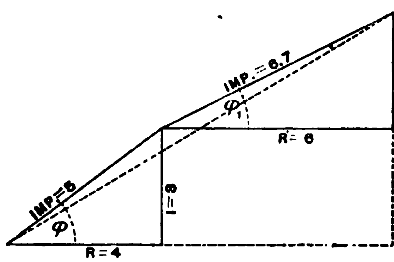


FIG. 52.

crepancy between apparent and real energy may also be very great. In practice $\cos \varphi$ may fall as low as 0.1 on single pieces of apparatus and ranges up under varying conditions of load to .95 or more.

These practical considerations naturally raise a question as to the effect of impedances in parallel. The joint impedance of two impedances in series must first be discussed.

The resistance of two resistances in parallel is of course familiar. If $R = 2$ ohms and $R' = 4$ ohms, then their joint resistance is the reciprocal of the sum of their reciprocals, thus,

$$(R + R') = \frac{1}{\frac{1}{2} + \frac{1}{4}} = 1\tfrac{1}{3} \text{ ohms.}$$

We have seen, however, that impedances cannot be added in the ordinary manner. If we take two impedances made up respectively of $R = 4$, $I = 3$, and $R' = 6$, $I' = 3$, we must proceed as in Fig. 52. The first impedance is 5, the second 6.70.

The true impedance of the two in series is given by the dotted lines and is 11.66, not 11.70. That is, the impedances must be added geometrically, since unless $\varphi = \varphi_1$ the arithmetical sum of the impedances does not represent the facts in the case. Similarly, while it is perfectly true that the joint impedance of two impedances in parallel is equal to the reciprocal of the sum of their reciprocals, the summation must be done as in Fig. 52 to take account of the difference of phase which may exist in the two branches. Taking the data just given, the reciprocals of the two impedances are .20 and .149 respectively. Drawing these on any convenient scale as in Fig. 53, preserving between them the angle due to the difference of phase as given by φ and φ_1, we find the geometrical sum of the recipro-

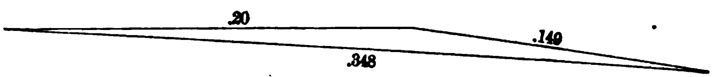


FIG. 53.

cals to be .348, of which the reciprocal is 2.87. This is the joint impedance of the two which we have thus geometrically added.

This same process can be extended to any number of impedances in parallel. It is important to note that since the currents in such cases are generally not in phase with each other, it usually happens that the sum of the currents in the branches differs from the current in the main circuit, as they are ordinarily measured. At any particular instant, however, there is strict equality between the whole current and its parts, the inequality appearing when the complete cycles with their phase differences are considered. It is in fact a prominent characteristic of alternating circuits that both currents and voltages are liable to violate all the traditions of continuous-current practice in a way apparently very erratic. Particularly is this the case when there is *capacity* in the circuit, a condition which we will now investigate.

By a circuit having capacity we mean one so constituted that E. M. F. applied to it stores up energy in the form of electrostatic stress, which starts this energy back in the form of current when the constraining E. M. F. is removed.

Such a condition exists whenever two conductors are separated by an insulating medium, or dielectric, as in

the ordinary condenser of Fig. 54. Here *A* and *B* are two metal plates separated by a layer, *C*, of some insulating material. If now these plates are connected to the terminals of a dynamo they become electrostatically charged. The electrostatic stress tends to draw the plates together and in addition sets up intense strains in the dielectric *C*, rendering potential thereby a certain amount of energy which flows into the apparatus in the form of electric current. This energy is returned as current if the original electromotive stress is removed and *A* and *B* are connected together. The medium behaves just as if it were a strained spring, and when it returns its energy to the circuit it does so spring-fashion with rapid

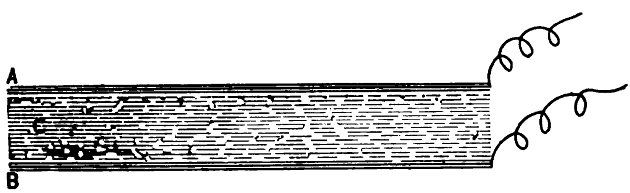


FIG. 54.

oscillations, dying out the more slowly the less resistance they encounter.

The capacity of such a condenser is the quantity of energy which it can store up as electrostatic strains in *C*. It is proportional to the area of the plates, to the E. M. F. producing the strains, and to the "dielectric constant" of *C*, that is, the coefficient which for that particular substance measures its power to take up electrostatic strains. Oddly enough the capacity decreases as *C* grows thicker, indicating that the intensity of the strain is the thing which counts rather than the volume of dielectric. Without knowing the exact character of electrostatic strain it is difficult to get a clear mechanical idea of the state of things which causes the energy stored to increase as the thickness of *C* diminishes. A similar condition, however, holds for a wire held tightly at one end and twisted at the other; the shorter the wire the more energy stored for a given angle of twist.

As in the case of inductance, for practical purposes the unit of capacity is taken in terms of unit pressure, *i. e.*, one volt. Unit capacity then, in terms of energy, is the capacity of con-

denser in which one watt second can be stored under an electromotive stress of one volt. This capacity is one *farad*, and as it is many thousand times larger than anything found in practice $\frac{1}{1000000}$ of it (the *microfarad*) is more often used.

When a condenser is used with an alternating current the rate at which energy is stored and delivered evidently increases with the frequency, or what is the same thing, for a given alternating E. M. F. the greater the frequency the greater the *current* received and delivered by the condenser.

Numerically the current in a condenser of capacity k farads, supplied by an E. M. F. of e volts at n cycles per second is

$$C = 2 \pi n e k,$$

which is simply the current due to e volts and k farads multiplied by the frequency expressed in angular measure. Thus if we have a 2 *microfarad* condenser fed by an alternating E. M. F. of 2,000 volts and 130 cycles per second the current flowing is

$$C = \frac{2{,}000 \times 6.28 \times 130 \times 2}{1{,}000{,}000} = 3.26 \text{ amperes.}$$

In such an alternating circuit then there will be a substantial current flowing in spite of the fact that there is a break in the conductor at the condenser. In short the circuit acts as if it had a resistance of $\frac{2{,}000}{3.26} = 613$ ohms, which is the *impedance* of the circuit. More exactly the impedance is $\frac{1}{2 \pi n k}$. It should be noted here that some writers refer to this fundamental condenser function $(2 \pi n) k$ as capacity-speed in the same way that they speak of $(2 \pi n) L$ as the inductance-speed.

To see the relation which this capacity-impedance bears to other impedances in the circuit it is necessary to look into the properties of the E. M. F. of the condenser. As energy is stored in the condenser the opposing stresses in it increase until the applied E. M. F. can no longer force current into it and the condenser is fully charged. At the moment, then, when current ceases to flow, the E. M. F. of the condenser tending to discharge it is at a maximum. Hence since the

one has a maximum as the other is zero, the E. M. F. of the condenser and the charging current are 90° apart in phase.

But the inductive E. M. F. is also 90° from the current, and as we have seen, lagging. It has its maximum when the current is *varying most rapidly*, and when the strength of current in a given direction is increasing, the inductive E. M. F. in the same direction is diminishing, as shown in Fig. 49. As regards capacity, however, the moment of maximum condenser E. M. F. in a given direction is that at which the current thereby becomes zero, so that as the current changes sign it has behind it the thrust of the full E. M. F. of the discharging condenser, while at the same moment as we have just seen the opposing inductive E. M. F. is at its maximum. Hence the E. M. F. of the condenser has a maximum in one direction when the inductive E. M. F. has its maximum in the other direction. The two are thus 180° apart in phase, and each being 90° from the current, the condenser E. M. F. must be regarded as 90° ahead of the current, just as the inductive E. M. F. is 90° behind it.

The condition of affairs is shown in Fig. 55. Here *a a* is the line of zero current and E. M. F. All quantities above this line may be regarded as +, and all below it as — ; *b* is a + wave of current to which appertains *c c* the curve of inductive E. M. F. lagging 90° behind the current, and *d d* the condenser E. M. F., leading the current 90°.

It is evident that these two E. M. Fs. always are opposing each other—when one is retarding the current the other is accelerating it and *vice versa*.

The condenser E. M. F. has no effect on the total energy of the circuit for the same reason that held good in respect to Fig. 49; it is obviously akin to a spring, alternately receiving and giving up energy, but absorbing next to none.

Capacity may be considered as *negative* inductance in many of its properties. If, as in Fig. 55, it is in amount exactly equivalent to the inductance, the total effect on the circuit is as if neither capacity nor inductance were in the circuit. In such case it is as if *C B*, Fig. 47, should be reduced to zero. The impressed E. M. F. then becomes equal to the effective E. M. F., the angle of lag vanishes and the circuit behaves as

if it contained resistance only. If the condenser E. M. F. is not quite large enough to annul the inductance it simply reduces it.

Fig. 56 illustrates the effect of varying amounts of capacity. In the main triangle *A B C*, the sides have the same

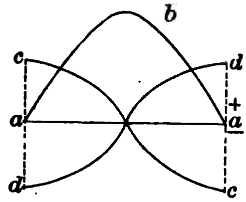


FIG. 55.

signification as in Fig. 47. Since the capacity E. M. F. is 180°, from, *i. e.*, directly opposite to, the inductive E. M. F., the effect of adding the capacity E. M. F. *C D*, is to reduce the effective inductance to *B D* and give as an impressed E. M. F. *A D* and an angle of lag φ_1. Now increasing *C D* to equal *C B*, the inductance is annulled, φ becomes zero, and the impressed

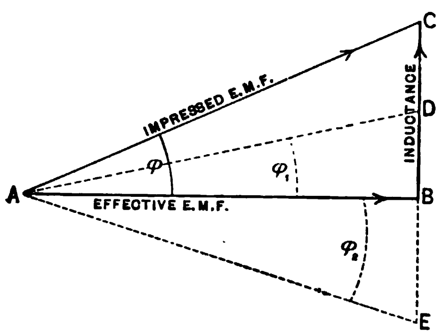


FIG. 56.

and effective E. M. Fs. are the same. Then increase *C D* still further so that it becomes *C E*. Now the inductance *C B* not only is neutralized but is replaced by a negative inductance *B E*. The angle of lag now becomes an angle of lead, φ_2, the necessary impressed E. M. F. rises to *A E*, and the circuit behaves as regards the relations between current, E. M. F., and energy, just as it did when affected by inductance. There is the same discrepancy between real and apparent energy, the

same necessity for more current to represent the same energy. But adding inductance now decreases the angle of lead. From a practical standpoint capacity by itself is objectionable, but capacity in a line containing inductance is sometimes a very material advantage.

The nature and reality of this curious phenomenon of "leading" current in an alternating circuit may be appreciated by an examination of Fig. 57. This shows the actual curves of current and E. M. F. taken from a dynamo working on a condenser in parallel with inductance. The maximum of the current wave is very obviously in advance of the maximum of the E. M. F. wave, though by a rather small amount

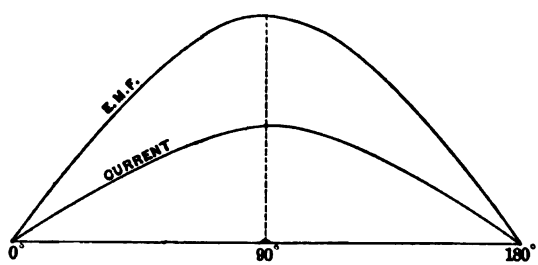


FIG. 57.

(actually about 6°). The capacity in this case was between 2 and 3 microfarads.

Treating capacity as a negative inductance enables us to compute its effects quite easily. We have already seen how to reckon the impedance of a condenser; using the word impedance here in its proper sense of apparent resistance by whatever caused. This quantity we can add geometrically to the ohmic resistance of a circuit and obtain the net impedance just as in Fig. 50. We must bear in mind, however, that the capacity E. M. F. is 180° from the inductance E. M. F., though each is at right angles to the effective E. M. F. which is concerned with the ohmic resistance.

Instead then of computing the total impedance as $\sqrt{r^2 + I^2}$, it becomes $\sqrt{r^2 + \left(\frac{1}{2 \pi n k}\right)^2}$, the second term under the radical being the square of the apparent resistance due to the capacity, just as I^2 expressed the square of the apparent resistance due to inductance.

Suppose for example we have a resistance of 100 ohms in series with a condenser of 4 microfarads capacity. The impressed E. M. F. is 2,000 volts at 130 cycles per second.

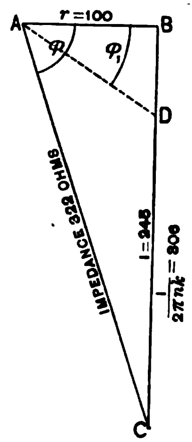


FIG. 58.

What is the total impedance, the resulting current, and the angle φ, in this case an angle of lead? Here

$$2\,\pi\,n k = \frac{6.28 \times 130 \times 4}{1{,}000{,}000} = .003266$$

$$\frac{1}{2\,\pi\,n k} = 306,$$

Laying off the resistance $A\,B$ in Fig. 58 as in Fig. 50 and drawing $\frac{1}{2\,\pi\,n\,k}$ to the same scale at right angles (downward to emphasize its opposition to the inductance of Fig. 50), we have for the length of the diagonal $A\ C$, which represents the total impedance, $\sqrt{100^2 + 306^2} = 322$ ohms. The current flowing is then, 6.21 amperes. The angle φ is determined as before by $\tan \varphi = \frac{306}{100} = 3.06$, whence $\varphi = 72°$, $\cos \varphi = .309$, so that we are dealing with a "power factor" like that produced by a heavy inductance, although the current leads the E. M. F. instead of lagging behind it. If we consider an

inductance in series with this circuit, we should have to reckon it upward in Fig. 58, thereby subtracting it from the former length $B\ C$.

Suppose for example for the given inductance $L = .3$ henry. Then $I = 2\ \pi\ n\ L = 245$. If in Fig. 58 we draw 245 on the scale already taken, upward from C, we shall reach the point D. $B\ D$ therefore is 61, and $A\ D$, the resulting impedance, is $\sqrt{100^2 + 61^2} = 117$ ohms. The new current is therefore $\frac{2,000}{117} = 17.09$ and as $\tan \varphi_1 = .61$, $\varphi_1 = 31°.5$, being still an angle of lead.

It is easy to see that for a certain value of I, the capacity effect and inductance effect would exactly balance each other. This value is obviously $2\ \pi\ n\ L = \frac{1}{2\ \pi\ n\ k}$, since then in Fig. 58, $B\ C - C\ D = 0$, and the impedance and resistance are the same thing, while φ becomes zero.

In actual circuits the capacity is seldom in series with the inductance. It is usually made up of the aggregated capacity of the line wires with air as the dielectric, the capacity of any underground cables that may be in circuit, and finally the capacity of the apparatus, transformers, motors, and the like, that may be in circuit. Generally the major part of the total inductance is in the apparatus rather than the line, and hence in parallel with the capacity. In many cases nearly all the inductance and capacity is due to the apparatus, and the two may be regarded as in parallel substantially at the ends of the line. The inductance of generators and transformers may amount to several henrys, while their capacity is by no means small, though very variable, like the inductance. For example, the capacity of a large high-voltage generator or transformer may often amount to several tenths of a microfarad. Armored or sheathed cable has a capacity of from a quarter to a half microfarad per mile. Altogether one may expect to find a capacity of several microfarads not infrequently and considerable fractions of a microfarad very often.

Suppose now we have in parallel a capacity A, Fig. 59, of 2 microfarads, and an inductance of .5 henry, the resistance connected with each being insignificant. Assuming as before 2,000 volts and 130 cycles, what is the total impedance of the com-

bination, and the resulting current? We have already seen how impedances in parallel are to be treated. In the case in hand the impedance of A is $\frac{1}{6.28 \times 130 \times .000,002} = 613$ ohms, and that of B is $6.28 \times 130 \times .5 = 408$ ohms. Now remembering that in adding impedances their geometrical sum is to be taken and that joint impedance is the reciprocal of the geometrical sum of the reciprocals of its components, we can proceed as follows: The reciprocal of 613 is .00163. This we will lay off to any convenient scale just as in Fig. 53. As it is capacity-impedance we will draw it downward for the sake of uniformity, making A B, Fig. 60. Now take the inductance.

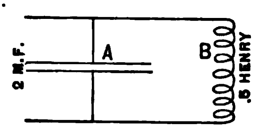


FIG. 59.

The reciprocal of 408 is .00245. As the inductance and capacity E. M. Fs. are here as before at an angle of 180°, we must draw this upward from B, giving us the distance B C. The geometrical sum is then $A\ C = .00082$, of which the reciprocal gives the resultant impedance as 1,219 ohms. Hence the net current in the line under 2,000 volts is $\frac{2,000}{1,219} = 1.6$ ampere. But under the same pressure the current in A would obviously be 3.26 amperes and that in the inductance B would be 4.90 amperes. We have then the curious phenomenon of a total current in the line smaller than that through either of the two impedances in circuit. It is as if A and B formed a local circuit by themselves in which the condenser A served as a species of generator. It is quite evident that the total energy of the system, however, is that due to the current in the line, so that the phases in A and B are greatly displaced. If the resistances in the circuit were quite negligible the net current in the line would be indefinitely small when $A = B$, that is, when $L = \frac{1}{k}$. Of course, however, the true impedances of both A and B are modified by the resistances, however small,

so that in Fig. 60 the impedances will always be at a small angle with the E. M. Fs. instead of being coincident. Hence the net current can never become zero, though when the impedances of A and B are large compared with the resistances, the line current will be very small when $L = \frac{1}{k}$.

This case is in sharp contrast to that in which condenser and inductance are in series with each other. For then the line current is increased as L approaches $\frac{1}{k}$ instead of becoming smaller relatively to the branch currents, although in each case the same relation between capacity and inductance gives

FIG. 60.

the maximum "power factor" on the circuit, since whatever the current, under this condition it depends most nearly on the resistance alone. When the resistance is quite perceptible in comparison with the impedances of A and B, we should form a resultant impedance with each, and then combine the two somewhat as in Fig. 52.

If then we have an inductive load of any kind in circuit, a condenser in parallel therewith will reduce the current on the line and thereby increase the "power factor" of the system. It does this, too, without any material loss of energy and without necessarily increasing the amount of current flowing through the inductance under a given E. M. F. on the line. Were condenser and inductance in series the power factor could likewise be improved up to a certain point, but trouble would be encountered in that the condenser would necessarily have

to be large enough to let pass enough current to supply the energy required in the inductance at full load.

In all practical cases the relations between resistance, capacity and inductance which have just been set forth, are somewhat modified by the existence of losses of energy in the circuit quite apart from these due merely to overcoming of resistance. Energy is required to reverse the magnetization of the iron cores of inductance coils, and to reverse the electric strains in the dielectric of condensers. It therefore happens that with a condenser in circuit the condenser current is not

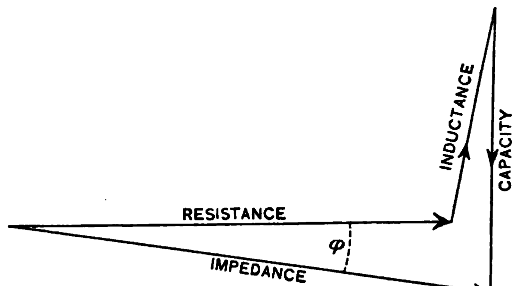


FIG. 61.

exactly 90° ahead of its impressed E. M. F., as shown in Fig. 55, but a trifle less, so that the current has a small component in phase with its E. M. F., thus supplying the energy in question. The deviation from 90° is generally but a small fraction of a degree. The same sort of thing happens when an inductance having an iron core is in circuit. However small the resistance, the lag still misses 90° by enough to take account of the energy required for magnetic losses. The variation from 90° in this case may amount to 30° or more. Hence the failure to take account of these energy losses in the example given on page 127.

It therefore comes to pass that in practically figuring the relations between resistance, capacity and inductance, one apparently deals with oblique-angled triangles. The result is that in adding inductance and capacity effects one seems not to get the simple results from Fig. 60, but something more like Fig. 61. Here it is clear that no combination of capacity and inductance can leave the circuit free from everything except resistance, for both the inductance and the capacity demand energy

in the circuit beyond that expended in the resistance. Evidently, however, φ may be reduced to zero if the relation between capacity and inductance is just right. Thus while the lag may be reduced to zero, no combination can dodge the energy losses.

Closely connected with this subject is the matter of resonance, which will be taken up in connection with the discussion of the line. Briefly the phenomenon is this: We have seen that the E. M. F. of a condenser is a maximum when the current is zero, so that as the current changes sign the thrust of the condenser E. M. F. is behind it. Now if the condenser E. M. F. synchronizes with this current, the impressed E. M. F. is added to it, imposes an added stress on the condenser during the next alternation, catches therefrom an additional kick as it passes through zero again, and so on. Thus the net effective E. M. F. is raised by the action of the condenser and would increase enormously but for its being frittered away in overcoming resistance and supplying such energy losses as we have just been considering. By avoiding these losses as far as possible one can actually raise the voltage on an alternating circuit to twenty-five or thirty times its nominal amount by employing a condenser of the proper capacity. Even when the impressed E. M. F. and the current are not quite in phase, one has always a component of the condenser E. M. F. tending to act in a similar manner. Whether it actually produces a sensible rise of voltage depends on its relations to the frequency and resistance with which it has to deal. In fact it is the addition of this same condenser E. M. F. to the circuit that enables one to neutralize inductive E. M. F. Whether or not the neutralization of inductance by capacity produces a real resonant rise of voltage depends on the frequency and whether the energy losses are small or large. If they are small enough to let the sum of the impressed and the condenser E. M. F. accumulate during several alternations there will be a noticeable increase of voltage, otherwise not.

We have now looked into the most important characteristics of alternating currents—those concerned with the phenomena of inductance and capacity.

It remains to note very briefly some other physical peculiarities that are of practical importance.

The most important single property of alternating current is the ease with which it can be changed inductively from one voltage to another. If a circuit carrying such a current is put in inductive relation with another circuit as in Fig. 4, Chap. I, the electromagnetic stresses set up by the first circuit can be utilized to produce alternating current of any desired voltage in the second circuit. The details of the operation will be taken up later; suffice it to say here that it is essentially the transformation of the electromagnetic energy due to one circuit into electrical energy in another circuit.

Alternating currents can be regulated in amount by putting inductance in the circuit without losing more than a very trifling amount of energy. This very property, however, is troublesome when an alternating current is used for magnetizing purposes. It is very difficult to get a large current to flow around a magnet core because of the high inductance, and even then the magnetic and other losses in the core are serious unless great care is taken. These difficulties have stood in the way of getting a good alternating motor until within the past few years, and even now such motors have to be designed and constructed with the greatest care to avoid trouble from inductance and iron losses. For certain classes of work, such as telegraphy, electrolytic operations, and to a less extent arc lighting, the alternating current is ill suited save under special conditions and with special apparatus. For the general purposes of electrical power transmission it is singularly well fitted, from the great ease with which transformations of voltage can be made, certain very valuable properties of the modern alternating motor, and the great simplicity and efficiency with which regulation can be effected. In addition there is some reason to believe that with equally good regulation of the voltage, incandescent lamps are subject to slightly less deterioration on an alternating circuit than when worked with continuous current.

CHAPTER V.

POWER TRANSMISSION BY ALTERNATING CURRENTS.

BROADLY considered, we may say that all systems of transmitting power by alternating currents are closely akin in principles and characteristics. The growth of the art, however, has proceeded along several lines, and certain conventional distinctions have come to be observed in considering the methods employed for rendering the alternating current applicable to the working conditions of power transmission.

Alternating systems are usually classified as either monophase or polyphase. By the former term is generally understood a system generating, transmitting and utilizing a simple alternating current such as shown in diagram in Fig. 40. By the latter is meant a system generating, transmitting and utilizing two or more such currents differing in phase and combined in various ways. As regards the systems, this distinction is sufficiently sharp, but as regards individual parts of such systems the line of demarcation is sometimes hazy, since a monophase current may be the source of derived polyphase currents, and on the other hand polyphase currents may be so combined as to give a monophase resultant. Such mixed systems may properly be called *heterophase.*

As regards apparatus, any device that performs all its functions in a normal manner when deriving its energy from a simple alternating current should be classified as monophase. If its functions require the co-operation of energy received from two or more alternating currents differing in phase, the apparatus is essentially polyphase.

For certain purposes the one system is best adapted, for certain other purposes the other is most advantageous, but the underlying principles are the same, and the apparatus has much the same general properties.

The material of alternating transmission work may be classified as follows, the transmission line itself being reserved for

discussion in another chapter in connection with other line work:

I. Generators.
II. Transformers.
III. Synchronous Motors.
IV. Induction Motors.

After a tolerably careful examination of the practical properties of this apparatus in its various forms, we shall be able to appreciate its application to the electrical transmission of power under various circumstances. Subsidiary apparatus of all kinds will be referred to in its proper place, and the divers systems that have been exploited can best be considered after we have, in a cold-blooded sort of way, looked into the characteristics of their component parts.

Alternating power transmission is now going through the stage of development that is inseparable from the rise of a comparatively new art—the planting time of "systems," if one may be allowed the simile. A little later we shall be able better to judge the quality of the crop. It is sufficiently certain already that the same sort of plant will not do equally well under all circumstances.

The principles of the alternating current dynamo have already been explained, but the constructional features of such machines are sufficiently distinct from those of continuous current dynamos to warrant examination in considerable detail.

The modifications peculiar to alternators are in general due to two causes; first, the general use of a fairly high frequency, and, second, the necessities of rather high voltage.

We have already seen that, while an ordinary continuous current dynamo fitted with collecting rings will give alternating current, the frequency is rather low. To secure a higher frequency it becomes necessary to increase the number of poles, the speed, or both. Increasing the number of the poles is the usual method employed, since continuous current dynamos are generally for the sake of keeping up the output operated at speeds as high as the conditions of economical use render desirable. So we usually find that for equal outputs alternators have many more poles.

For example, belt-driven continuous current dynamos of 100

to 500 kilowatts usually run at speeds from 600 down to 300, and have four or six poles, while modern alternators of similar size and speed have from 12 to 24 poles, thus adapting them for a frequency of 30~ to 60~. Machines for the older frequencies of 120~ to 140~ were usually even more liberally provided with poles unless driven at speeds considerably above those mentioned. The general appearance and design of a typical modern alternator is shown in outline in Fig. 62. This

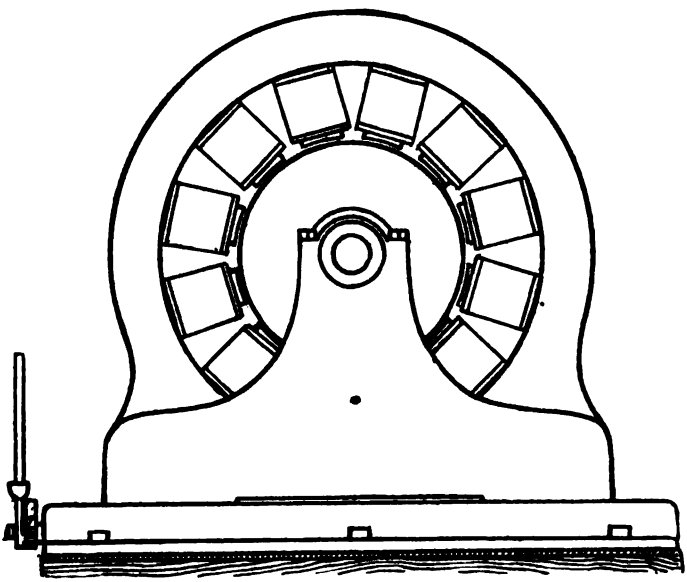


FIG. 62.

is a 150-KW generator running at 600 revolutions per minute, and shows admirably the general characteristics of rather numerous poles, low base, and massive bearings, that nowadays belong in common to machines by nearly all makers. Such alternators usually have very powerful field magnets, and the projecting pole-pieces are often built up of iron plates like the armature, and for the same purpose of preventing eddy currents in the iron. The ring of field magnets is split on the level of the centre of the shaft, for convenience in removing the armature. The weight of generators of the output named is usually in the neighborhood of seven tons.

This same general type is adhered to whatever the nature or voltage of the armature winding, save in the case of special machines.

The winding of a modern alternator is nearly always widely distinct from continuous-current windings. In alternators the voltage is generally from 1000 volts up, seldom below 500 volts, and to obtain this the windings corresponding to the numerous poles are almost universally connected in series instead of in parallel.

This necessitates specially connecting the armature coils in a very characteristic way. For when a given armature

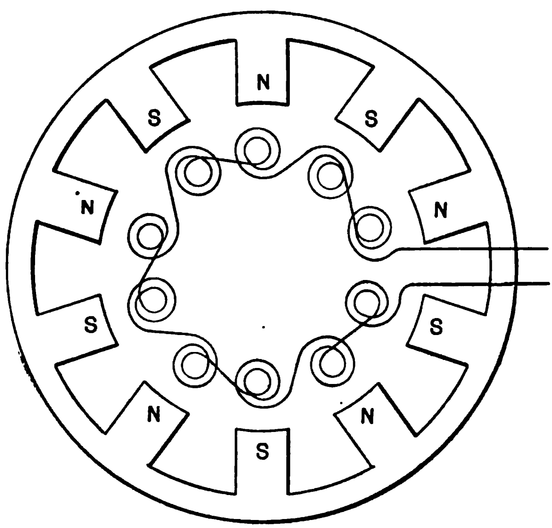


FIG. 63.

coil is approaching one of the north poles of the field magnet and is generating current in a given direction, the next armature coil is necessarily approaching the neighboring south pole, and if wound in the same direction as the first coil would generate a current flowing in the opposite direction. Hence if all the armatures coils are to be in series, they must be wound alternately in opposite directions, as shown in Fig. 63. This arrangement throws in series the E. M. Fs. generated by all the armature coils. Sometimes for convenience the halves of the armature are connected in parallel, thus giving

half the voltage and twice the current by a simple change in connections. Fig. 64 shows in diagram such a winding for a 16-pole field, and its relation to the collecting rings. Note that each half of the winding preserves the characteristics shown in Fig. 63.

In practical machines as built to-day, the armature coils are nearly always bedded in slots in the armature core. The early American machines were generally built with smooth armature cores, and upon these flat coils were laid and held in place by an elaborate system of binding wires. This construction has been virtually abandoned by all the principal manu-

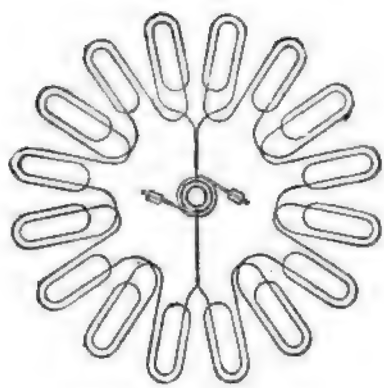


FIG. 64.

facturers in favor of the so-called "iron-clad" armature, which has the double advantage of great mechanical solidity and of permitting the armature coils to be wound in forms thoroughly insulated, and then dropped into place in their slots and firmly wedged in position. The winding is therefore very little liable to damage and easily replaced if necessary.

The slotted armature cores are variously arranged in different machines, but always with the same object in view.

Fig. 65 shows one widely used arrangement of slots. Here the coils are wound in forms and thoroughly insulated. They are then pushed into place in the previously insulated slot, each coil enclosing a single armature tooth. When firmly in place the insulating material is put into position above them and a hard wood wedge is driven into the dove-tailed upper portion of the slot, holding the coils and their surrounding

insulation permanently in place. The coils here shown consist of only four turns of heavy wire. Often there are many more turns per coil, and sometimes the round wire is replaced by rectangular bars. For use with raising transformers each coil sometimes consists of a single turn of bar copper, but whatever the nature of the coil the slots are arranged much as shown below.

Another excellent form of slotted armature is shown in Fig. 66. The coils are, as in the case just mentioned,

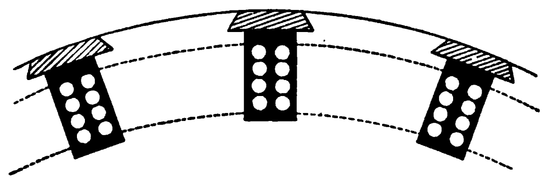


FIG. 65.

wound in forms and solidly insulated. They are then sprung over the armature teeth into place and tightly wedged. The slots are carefully insulated also, and by the time the winding is completely assembled it is so thoroughly insulated that repairs are few and far between. The special peculiarity of this form of core is that the outer corners of the teeth are cut away, so that the coils come more gradually into the field of

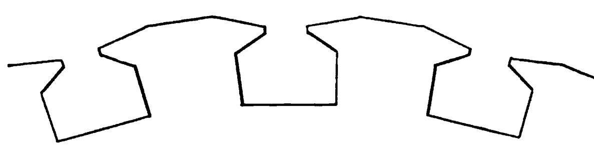


FIG. 66.

the pole-pieces than if the edges were sharp. The object of this device is to obtain a curve of E. M. F. more nearly according with the sine wave form, and experience shows that the plan works successfully. Without such precautions the E. M. F. curve is very likely to be quite irregular.

Nearly all modern alternating windings are, like those just indicated, of the drum type. The Gramme winding is seldom or never employed, as it is hard to wind and repair and has, for alternators, no compensating advantages. Nor has the

flat coil winding without iron core found a permanent place in American practice, although it is widely used abroad.

The flat coil is well exemplified in the form introduced by Ferranti, of which the armature is shown in Fig. 67. The thin coils revolve in the space between two opposite crowns of field magnets. The winding is connected as in Fig. 64, which not only enables the same armature to be reconnected for two voltages, but if extraordinary voltages are to be attempted,

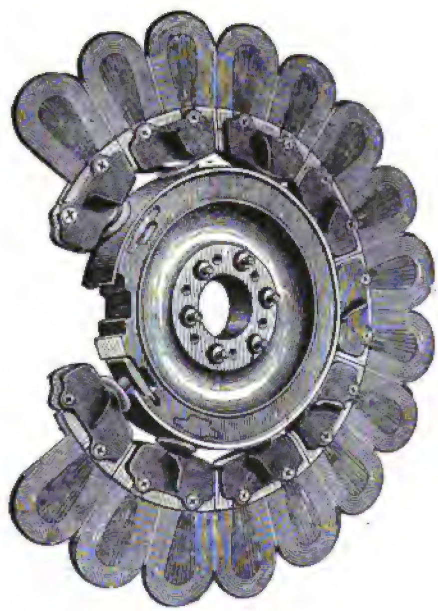


FIG. 67.

keeps armature coils of widely differing potential far apart in the structure. The Ferranti type of armature, being without iron core, has a very low inductance, which property is often highly desirable. There is, however, considerable likelihood of eddy currents in the armature conductors unless they are individually very thin, and for this and obvious mechanical reasons American designers have adhered to the iron-clad armature, which is admirable mechanically and magnetically, and have taken other means to get out of the difficulty of its high inductance.

As in other dynamos, the theoretical E. M. F. generated by an alternator depends on the strength of the magnetic field, the number of armature conductors under induction, and the speed at which they are driven through the field. As an alternator receives load the E. M. F. at its terminals is reduced by three several causes.

First, there is a loss of voltage due to energy lost in the armature conductors. This depends simply on the current and resistance and is numerically equal to CR.

Second, there is self-induction in the armature windings, which, as we have already seen, involves an inductive E. M. F., lagging 90° behind the impressed E. M. F. The effect of this is to partly neutralize the impressed E. M. F.,

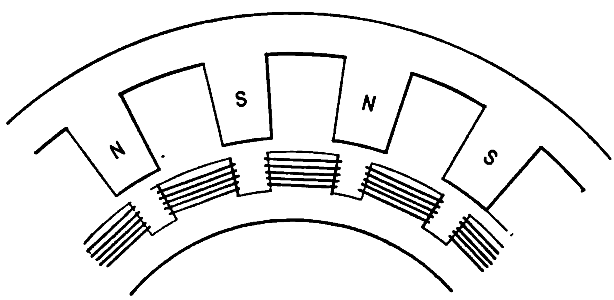


FIG. 68.

as in all cases of inductance. The amount of this disturbance depends on the frequency and the magnetic relation of the armature coils to each other and to the field magnets. This relation of course varies according to the relative position of the armature teeth which carry the coils. In Fig. 68, purposely shown with somewhat exaggerated teeth, the armature is in the position of minimum inductance, for the magnetic field set up by the armature coils is not here much strengthened by the presence of the pole-pieces. If, however, the armature were shifted forward or backward so that each tooth would be just opposite a pole-piece, the field from the armature coils would traverse an almost complete loop of iron and the inductance of the armature would be a maximum. In this position the armature teeth might be almost as good magnet poles as the field poles themselves; at all events, con-

secutive teeth would be united by an almost continuous iron core, and the armature inductance would be very high.

One of the best ways of reducing this inductance and its train of troubles is to make the magnetization due to the field magnets as strong as is practicable. This not only utilizes the iron of the field magnets and armature to the best advantage, but, so to speak, pre-empts its power of receiving magnetization so that the current about the armature teeth finds a poor field for its inductive operations. In addition, this strengthening of the field enables the required E. M. F. to be obtained

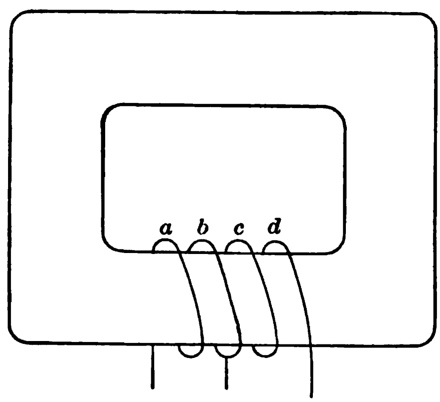


FIG. 69.

with fewer turns per tooth. This of itself is a great advantage, since increasing the number of turns in an iron-cored coil runs up the inductance with appalling rapidity. A glance at Fig. 69 will show the reason why. Suppose we have a looped iron core wound with four turns of wire, *a*, *b*, *c*, *d*. If we pass a certain alternating current around two turns, *a* and *b*, we shall have a certain inductance due to the reaction of the change in magnetism on these two coils. Now pass the same current around all four coils. The magnetization will be approximately doubled and the number of turns on which it acts will also be doubled. That is, each coil is acted upon by double the force and there are twice as many total coils. Hence the total inductance will be about four times as great as at first, and in general it will increase with the square of the number of turns. If, however, as just suggested, the

core is nearly saturated already, adding the two extra turns, *c* and *d*, will not anywhere nearly double the magnetization, since iron already magnetized responds less and less to additional magnetizing force as this force increases.

Hence, as we shall see later, diminishing the number of armature turns that can act conjointly in producing effective magnetization lowers the inductance very rapidly.

The third disturbing cause which tends to reduce the effective E. M. F. of an alternator is the reaction of the armature current, through the resulting magnetization, on the field magnets. We have already seen that when a closed coil is driven into and out of a magnetic field the induced current is always in such direction as to cause work to be done in driving the coil. But, since the current due to entering the field is equal and opposite to that produced in leaving the field, the total magnetizations due to these currents are equal and opposite, and if one opposes the field due to a pole-piece the other will in an equal degree strengthen that field. Hence, provided these two actions are applied alike; *i. e.*, are symmetrical with respect to the field, the total effect of armature current will be neither to weaken nor strengthen the field.

In practice the effect of the armature reaction is two-fold. If the current be nearly in phase with the E. M. F. the main result of the magnetic field set up by the armature is to distort that due to the field without greatly weakening it as a whole. The result of this distortion is that the E. M. F. does not increase and decrease steadily following a sine wave, but becomes irregular. The working E. M. F., as measured on a voltmeter, changes but a trifle, but the maximum E. M. F. becomes subject to great variations. Fig. 70 shows in a very striking manner the result of field distortion from a purely non-inductive load. Here *a* is the E. M. F. curve on open circuit and *b* is the curve as modified by the armature reaction at nearly full load. The arrow shows the direction of rotation of the armature. In this case the maximum voltage was increased about 30 per cent., while the measured voltage was nearly constant. Bearing in mind that the E. M. F. at any moment is due to the *rate of change* of the magnetic induction through the armature, and not to the

absolute amount of that induction, it is tolerably obvious that the effect of field distortion due to armature reaction may vary widely according to the shape and position of both the pole-pieces and the armature teeth. It may increase the maximum voltage as above, or decrease it fully as much, but if it is of any considerable magnitude it always deforms the E. M. F. wave very materially.

If, however, through armature inductance or inductive load the current lags behind the E.M.F., we have a very different state of affairs. The current reaches its maximum after the

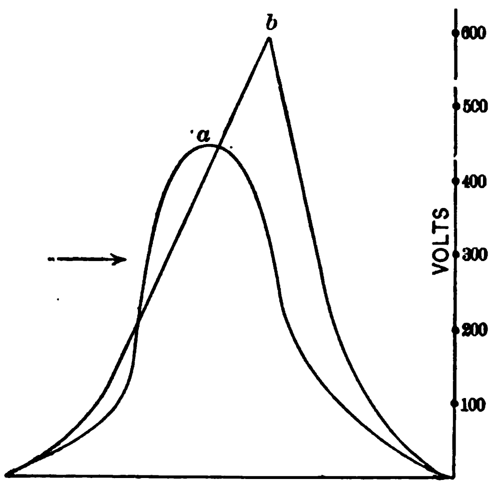


FIG. 70.

armature coil has passed beyond the position of maximum E. M. F., and the net magnetization produced by it chokes back the field, at the same time distorting it.

The magnetizing and demagnetizing effects of the armature current no longer can balance each other, for they are unsymmetrical with respect to the poles. If the angle of lag is large the result will be a very serious weakening of the field, and a correspondingly large drop in the effective voltage. For example, a certain alternator of 120 KW output has 40 turns of wire per armature tooth, carrying a normal full load current of 60 amperes. There is thus a possible demagnetizing force of 2,400 ampere-turns at full load. The ampere-turns per pole-

piece in the same machine are 3,600, so that if the current should lag enough to give the armature reaction full play, as might happen from excessive armature inductance alone, the total net magnetizing force would be reduced to a third of its normal amount and the resulting voltage to a half or less. It is in fact common enough to find alternators that require from 50 to 100 per cent. increase in the exciting ampere-turns to hold them at normal voltage under a full load current lagging even 15° or 20°.

Between inductance and armature reaction the effective E. M. F. of alternators generally falls off rapidly under load,

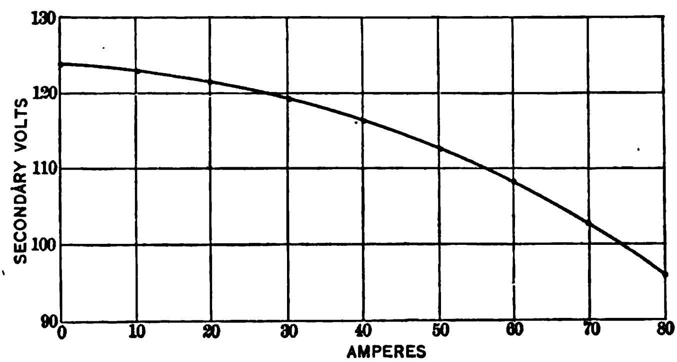


FIG. 71.

unless special care be taken with the design. The loss from ohmic resistance is usually trivial compared with those just named. It is in fact perfectly practicable to build an alternator with inductance and armature reaction so exaggerated, that a very slight increase in current will cut down the voltage so rapidly as to keep the current virtually constant. This plan was successfully carried out in the remarkable Stanley alternating arc machine of a few years ago.

In this case the current varied only about 10 per cent., while the voltage varied between a few volts and over 2,000. An automatic short-circuiting switch was provided to avert dangerous rise of voltage in case of an accidental open circuit.

In so-called constant potential alternators, as usually built, the inherent regulation is by no means good. Fig. 71 gives an excellent idea of the performance of some of the earlier

machines in this respect, and it is about what one would find in many alternators now in service, except for their compound winding.

It has often been held that high inductance and large armature reaction are desirable in alternators in order to prevent burn-outs in case of accidental short circuits. While it is perfectly true that sufficiently crude armature design does produce this effect, by limiting the possible current, it is equally true that a machine with sufficient inductance and reaction to serve as a practical safeguard will regulate so atrociously as to be under most circumstances incapable of decent commercial service under present conditions. When it was sufficient for an alternator to give current, that with sufficient hand regulation could supply house to house transformers most of the time, high inductance machines, which are easy and cheap to build, answered the purpose.

At present, when the importance of good regulation is generally understood, and most large alternating plants must look forward to assuming a motor load, low inductance machines with small armature reaction are essential for first class service. For power transmission plants with heavy mixed loads of lights and motors, no other class of machine should be tolerated, or can be used without incessant annoyance.

Most even of the older alternators are compound-wound to compensate for armature effects, and are thus enabled to work successfully up to outputs at which the voltage begins to fall off too fast to be thus compensated. So long as the compounding process actually gives good regulation, it is useful and enables the generators to be worked at a high output. As a matter of fact when used with generators of the older type, even compounding left much to be desired. As alternating practice has gradually improved, compound-wound alternators have been more skillfully designed, and recent machines give on non-inductive load a very fair approximation to constant potential. Fig. 72 shows the E. M. F. of a modern over-compounded alternator at varying load. If, however, the current has even a moderate lag behind the E. M. F., owing to inductance in the machine or the load, the machine will no longer give constant potential, and the voltage may fall off rapidly as the load comes on, as shown in the cut. The reason for this we have

already found in the extra increase of field excitation necessary to compensate for the demagnetizing effect of armature reaction. Incidentally if the current commuted to supply the series field lags much, the process of commutation cannot go on normally without adjusting the brushes to compensate for the lag.

Therefore for inductive load the compounding has to be greatly increased, and even then is correct only for a particular inductance.

It must be understood that alternators are compounded on the same general principles as continuous current machines, except

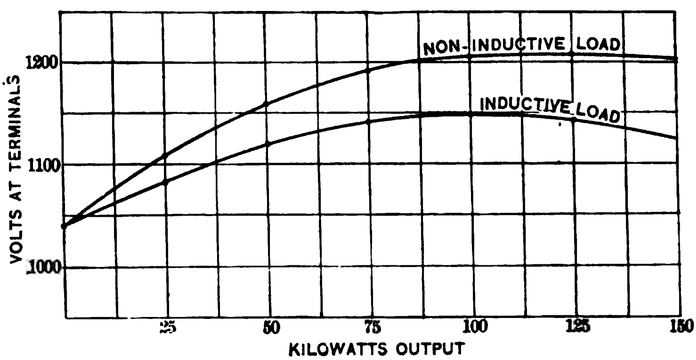


FIG. 72.

that instead of the current for the series winding being derived from the general commutator of the dynamo, it is generally obtained from a simple special commutator. A shunt around this commutator diverts most of the main current, while a portion is rectified and passed around the fields. Fig. 73 shows in diagram a common compounding arrangement. The two collecting rings *A* and *B* with the commutator *C* are mounted on the armature shaft. Brushes on *A* and *B* take off the alternating current. One of these rings, *A*, leads directly to line. The current going to the other ring is divided, part passing around *C* through the resistance box *D*, and part being rectified by the commutator for use in the series field. This commutator has as many segments as there are pairs of poles in the field, the alternate sections being electrically united.

By varying the resistance *D*, the amount of current diverted into the field can be varied and the compounding may thus be arranged to keep the voltage constant at the terminals or at any point on the line. A similar change in *D* may be made to adjust the compounding for inductive load of any given power factor.

For non-inductive loads, or for inductive loads, of constant

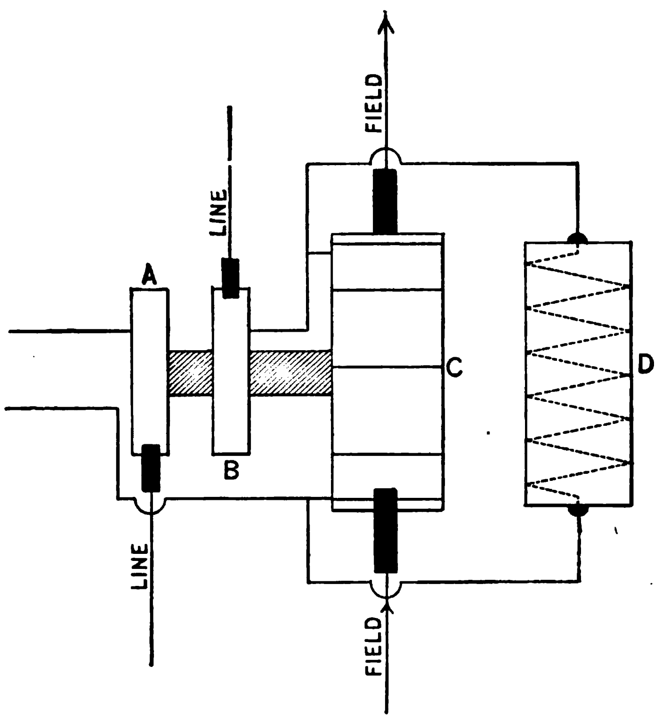


FIG. 73.

power factor, compounding gives good results, but for a load of widely varying power factor it is simply worthless unless supplemented by hand regulation.

If compounding is to be successfully used for keeping constant potential on a circuit of lights and motors subject to considerable variations in the power factor, it must be applied to a generator of very low inductance and armature reaction. Otherwise no adjustment of the compounding for any particu-

lar power factor will give approximately constant potential when the power factor varies.

For example it would be hopeless to attempt to compound an alternator having a characteristic like Fig. 71, so that it would be tolerable on a commercial circuit of lights and motors. On the other hand, a generator having a voltage characteristic like Fig. 74, could readily be so compounded. Here the fall in voltage at constant field excitation, from no load to full load (non-inductive), is about 3½ per cent. Under inductive load this fall would be increased considerably, but from the usual

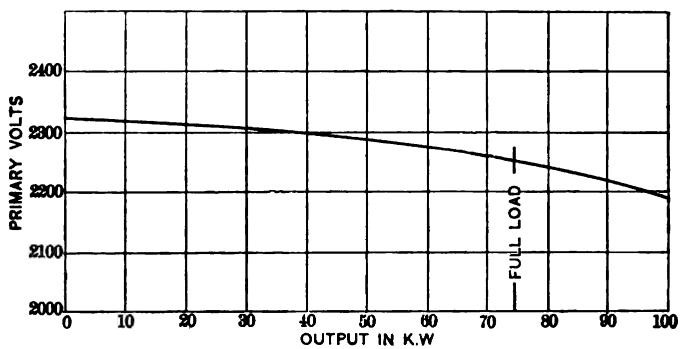


FIG. 74.

ratio of inductive drop to armature reaction found in the best modern generators, the variation for the power factors likely to be encountered with a mixed load would be somewhat smaller than the original drop. The total variation from no load to full inductive load would then be between 6 and 7 per cent., and with compounding adroitly adjusted for average conditions the greatest variation from normal voltage could easily be brought within 2 per cent. A little intelligent hand regulation at certain times of the day would improve even this good result.

These considerations apply to polyphase as well as to monophase generators. The advent of polyphase work has done much to improve all alternators, and especially with respect to regulation.

The generation of polyphase alternating currents is a very simple matter. The object in view is the production of two or

more similar currents differing in phase by some convenient amount, usually 60° or 90°. To obtain two currents 90° apart in phase, it is only necessary to clamp together the shafts of two common alternators, so that, for a construction like Fig. 65, the slots of one armature would be opposite the teeth of

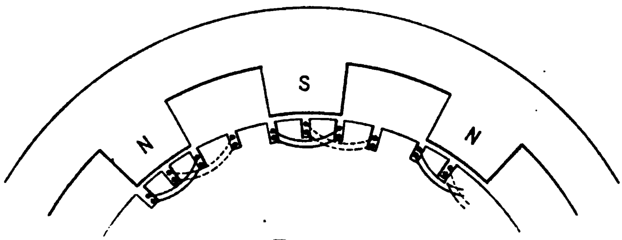


FIG. 75.

the other armature. The armatures would then give currents 90° apart in phase. Such combination alternators were built for the Columbian Exposition by the Westinghouse Company, and were used for the principal lighting and power circuits. These structures are, however, expensive for the output obtained, and the two windings are nearly always put on a single armature core, and spaced as just described. Fig. 75 shows a very simple

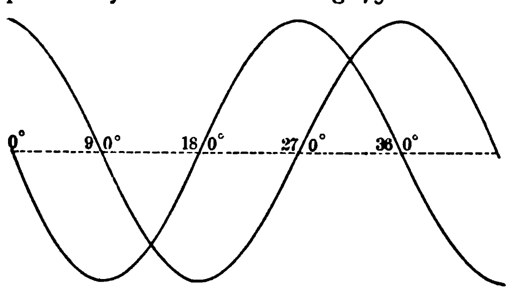


FIG. 76.

winding of this character. There are four times as many armature slots as there are field poles. Each coil spans two teeth. The coils shown by solid lines form one phase winding, the dotted coils the other phase winding. Each set of coils is connected as an ordinary monophase winding, and the terminals are brought out to two pairs of collecting rings. Such a winding gives two simple alternating currents related in phase as shown in Fig. 76. The armature core is very fully occupied

by the two windings, rather more advantageously than it could be by a single winding, so that the machine gives a somewhat better output as a two-phaser than would be possible with a simple alternator of the same dimensions. And, what is of more importance, the regulation of the machine as a two-phaser is much better than it would be as a single-phaser. In the first place the armature inductance is greatly reduced by the distribution of the windings and the reduction of the ampere-turns per armature tooth. Second, the same causes act to cut down the armature reaction in case of a lagging current. Anything that improves the intrinsic regulation also means greater output for unimproved regulation.

So, aside from the value of polyphase currents for motor purposes, which we shall presently examine, polyphase winding is valuable on its own account as increasing output and improving regulation. In fact diphase windings were devised for this purpose before their importance in the operation of motors became generally known.

The value of a subdivided winding in reducing inductance and armature reaction was greatly emphasized by the introduction of polyphase generators, and it was a short step from windings like Fig. 75, having one coil and virtually one tooth per phase per pole, to windings in which each phase winding is split up into several sets of coils in adjacent slots, thereby still further decreasing the effective inductance and armature reaction. Such windings may be called *polyodontal*, from their several teeth per phase per pole, and are very generally used in the best recent machines. A fine example of this class of winding is shown in Fig. 77. This is a quarter section of the armature of one of the 5,000 HP Niagara generators, showing a portion of one coil belonging to a single phase. The full winding is composed of two conductors per slot, half the total slots, in alternate groups, belonging to each phase.

Such complete subdivision of the coils results in low inductance and a very low armature reaction. A similar winding could be used for a monophase generator, and will have to be employed if monophase machines come to be used extensively for motor purposes. The form of armature slot used for polyodontal windings is shown in Fig. 78, a single segment of one of the core plates of the armature of the Niagara two-

phaser. The appearance of one of these great machines complete is admirably shown in the frontispiece, showing the interior of the Niagara station. The field magnets are revolved instead of the armature, although they are exterior to

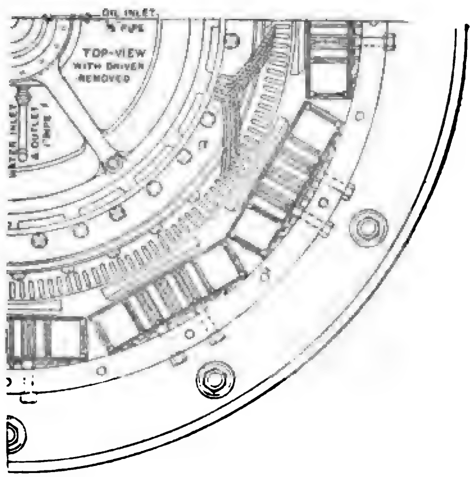


FIG. 77.

it. A very powerful fly-wheel effect is gained by this arrangement, since the weight of the revolving structure, turning at 250 r. p. m., is about 75 tons, half of this being in the field itself. This is about 12 feet in diameter, a single forged steel

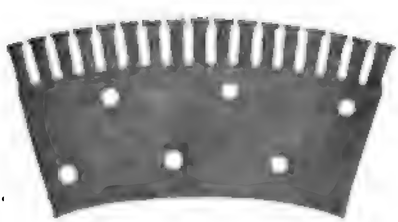


FIG. 78.

ring with twelve massive pole-pieces secured to its inner face. The normal voltage of the machine is about 2,250, and the frequency is 25 ~. The stationary armature is provided with six ample ventilating ducts, through which air is forced by

the revolving field. Fig. 79 shows a vertical section of the whole apparatus with its shaft and upper bearings. A hundred and forty feet below the generator is the turbine which supports by hydraulic pressure the weight of the revolving mass, save a ton or two residual weight, which may be either positive or negative, and which is taken care of by a thrust bearing.

The full load of this generator is 775 amperes on each of the

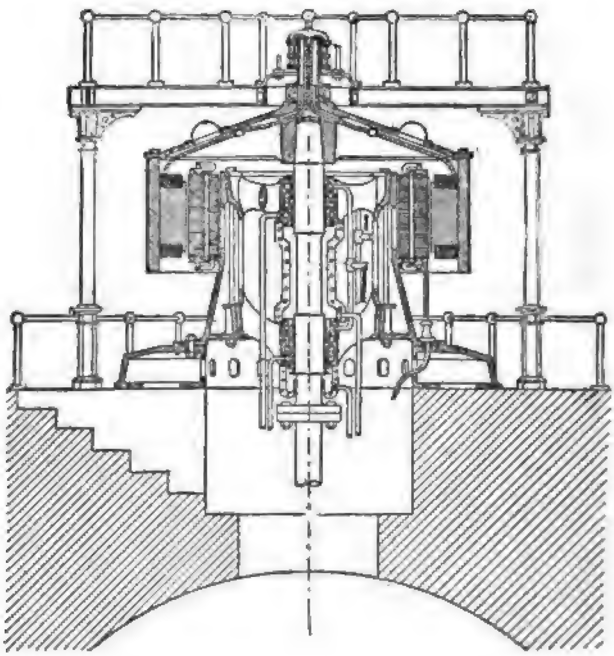


FIG. 79.

two circuits, and at this load the commercial efficiency is very nearly 97 per cent.—the highest figure yet touched by any kind of generator. The exciting current for the fields is derived from a rotary transformer, and is led into the revolving magnets through a pair of collecting rings shown in Fig. 79 at the extreme top of the shaft. The armature current is of course taken from stationary binding posts. Altogether the Niagara machine is a magnificent specimen of polyphase construction.

When three-phase currents instead of two-phase are to be generated, separate armatures are out of the question, and a winding similar to that of Fig. 75 is frequently employed. To obtain the three currents, however, three separate windings are employed, arranged as in Fig. 80. The coils are connected

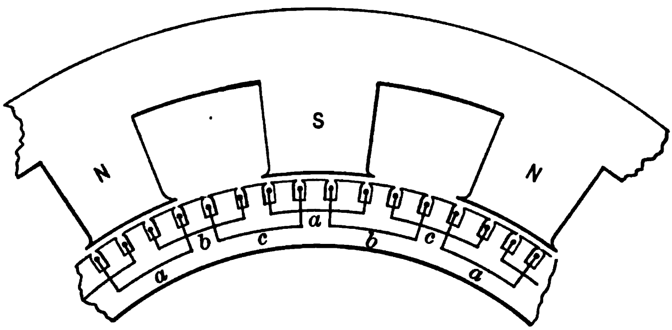


FIG. 80.

so that *a*, *a*, *a*, etc., form one phase winding, *b*, *b*, etc., a second, and *c*, *c*, etc., the third. The close similarity of this winding to the two-phase shown in Fig. 75 is at once apparent.

It is worth noting that these three windings are spaced 60° apart, instead of 90°, as in a winding for two phases. Naturally

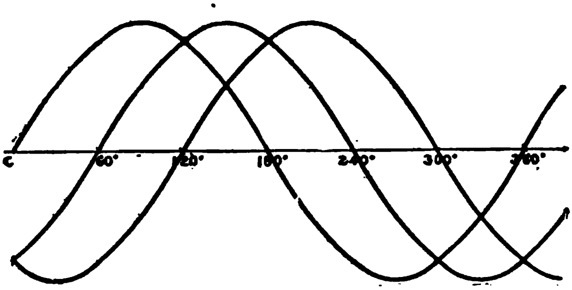


FIG. 81.

therefore the currents generated would be different in phase by only 60°, giving the arrangement of currents shown in Fig. 81. This is homologous with the two-phase current system of Fig. 76.

In practice it is necessary, however, to have the sym-

metrical arrangement of phases given by three similar currents 120° apart. This is very easily obtained in the external circuit by winding one set of the armature coils in a direction reversed from the other two, or by merely reversing the terminals in making connections. The result of this is a true three-phase current, such as is shown in diagram in Fig. 82. It has now the curious property that at all times the system is simultaneously carrying currents substantially equal in both directions, as will readily appear from inspection of the curves. With such a current it is usual to combine the circuits cor-

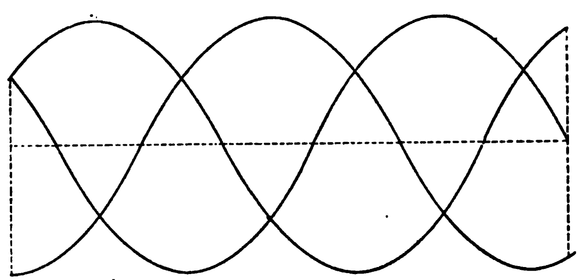


FIG. 82.

responding to the several armature windings. Otherwise we would be compelled to deal with circuits of six wires, and the generator would have six collecting rings.

As might be expected, the subdivision of windings in a three-phase armature results in small inductance and armature reaction, smaller in fact than would be found in a similar two-phase winding. Nevertheless experience shows that if the armature has only a single coil per phase per pole, the reaction is too great for first-class regulation, and the curve of E. M. F. is rather too wide a departure from the sine wave. It is quite usual, therefore, to adopt the polyodontal construction with from two to four coils per phase per pole. A machine carefully designed on these lines can be made to give excellent regulation, with voltage not varying more than 3 or 4 per cent. from no load to full non-inductive load, and is capable of giving a very close approximation to a true sinusoidal wave, a valuable characteristic for long distance transmission. Fig. 83 shows the wave form given by one of these polyodontal three-phasers.

The full curve shows the actual E. M. F., the dotted line the corresponding sine curve, and the irregular line at the base of the figure the difference between the two.

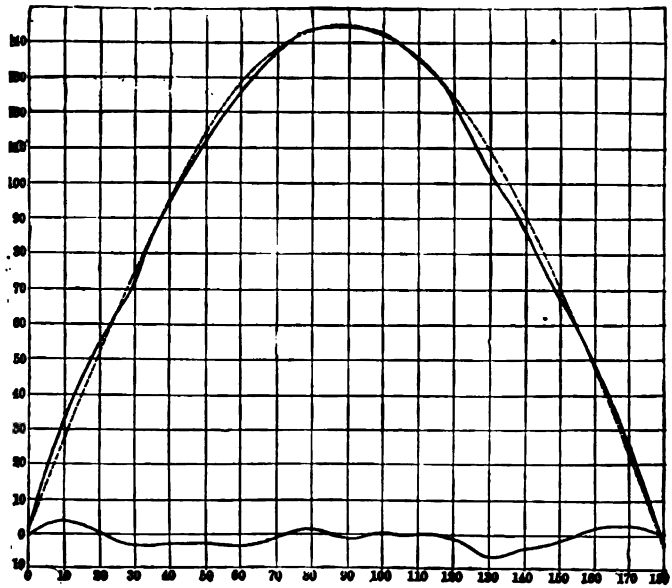


FIG. 83.

There are several methods of connecting a three-phase winding to its external circuit. The two chiefly used are generally known as the "star" and "mesh" connections. In the former

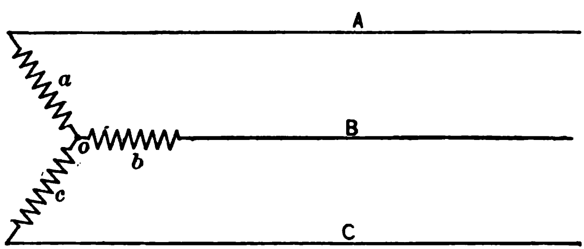


FIG. 84.

one end of each of the three windings is brought to a common junction, and the three remaining ends are connected to three line wires. The three lines then serve in turn as outgoing and

return circuits, the maximum current shifting in regular rotation from one to the others in succession. The three E. M. Fs. in the three coils differ in phase by 120°, owing to the reversal of which we have spoken. We may draw the star connection diagrammatically in Fig. 84, drawing the three coils *a b c* 120° apart to show the relation of the E. M. Fs. and currents, although they lie on the armature as shown in Fig. 80. Three of the terminals meet at the point *o*, the others are connected respectively to the lines *A*, *B*, *C*. As the three windings on the armature are alike, the E. M. Fs. generated by the three coils are equal. So if each winding *a*, *b*, *c*, is designed for 1,000 volts, that will be the voltage between the point *o* and each of

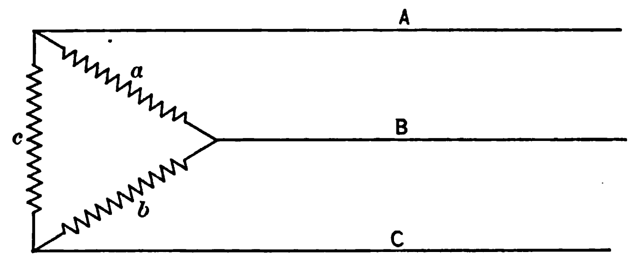


FIG. 85.

the three lines *A*, *B*, *C*. Clearly, however, the voltage between any two of these lines, as *A* and *B*, is a very different matter, since it results from the addition of the voltages of *a* and *b*, which are, however, 120° apart in phase. They must then be added geometrically. Now the chord of 120° is $\sqrt{3}$ times the radius, so that the geometrical sum of the voltages *a* and *b*, 120° apart, is 1.732 times either of them. The voltage then between *A* and *B* in the case in hand is 1,732. The same is evidently true of the other pairs of lines *B*, *C*, and *C*, *A*.

The other ordinary three-phase connection is the mesh, in which the six terminals of the three coils are united two and two, and the lines are connected to the three points of junction. This arrangement is shown diagrammatically in Fig. 85. Here each coil must generate the full E. M. F. between any two of the lines, but the current in any line, as *B*, is made up of the geometrical sum of the currents in *a* and *b*, differing in phase, just as the E. M. F. between lines in Fig. 84 was made

up of the sum of two E. M. Fs. The current in B being then so constituted, is $\sqrt{3}$ times the current in a or b, and so on for the other lines. In the mesh connection we deal with resultant currents just as in the star we find resultant E. M. Fs.

An armature designed for a given working voltage, measured in the ordinary way between lines, would, if planned for star connection, have fewer turns of larger wire than if intended for mesh connection. This is sometimes convenient, and is useful in keeping the voltage between coils low. The mesh connection on the other hand has more turns of smaller wire, as the current is diminished while the E. M. F. in each coil is the full E. M. F. between lines. This property is useful under certain conditions, as it makes the E. M. F. between any two lines somewhat less dependent on the actions going on in the other pairs of lines. The same windings can of course be connected either star or mesh, according to the dictates of convenience. Both these combination circuits have in common one immensely valuable property. They require for the transmission of a given amount of energy at a given percentage of loss, only 75 per cent. of the weight of copper required for the same transmission at the same working voltage, by continuous current or by any alternating system having two wires per phase. That is, if 100 tons of copper are required for a given transmission by continuous current, single-phase alternating, two phase with two circuits, or three phase with three circuits, 75 tons will suffice for the same transmission by the star or mesh three-phase circuit without any increased loss of energy. A similar saving can be effected by the use of some other polyphase combination circuits, such as a two-phase circuit with one wire common to both phases, but it happens that the three-phase combination is the one least open to practical objections.

In actual working the two-phase system is nearly always installed with a complete circuit per phase, unless for short connections to apparatus; the three-phase system is used with the star or mesh combination, except for occasional special work, and the more complicated polyphase systems are practically not used at all.

In speaking of the voltage of an alternating circuit, it must be borne in mind that we do not mean the voltage corresponding to the extreme crest of the E. M. F. wave, but that volt-

age which, multiplied by the current in a non-inductive circuit, equals the energy in that circuit. This effective working voltage bears no fixed relation to the real maximum voltage, since their ratio evidently varies with the shape of the E. M. F. wave. For a sine wave the ratio is 1.414, so that an alternating working pressure of 1,000 volts means a maximum voltage of 1,414. As may be judged from Fig. 83, this ratio is very nearly true for the best modern alternators.

Save in rare instances the work of power transmission is done by two-phase or three-phase currents. Abroad some pure single-phase plants are in operation with fairly good results, but the difficulty of getting good single-phase motors has so far

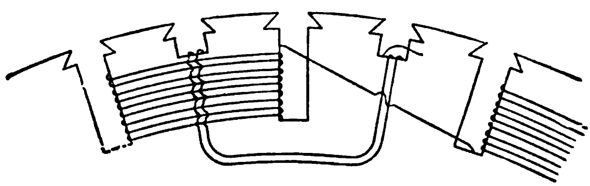


FIG. 86.

rather checked development along this line. In this country the "monocyclic" system has been introduced for simplicity in the connections for lighting purposes, and in a few cases this apparatus is used largely for motor purposes.

In this system there is a main armature winding to which the lighting circuits are connected as in ordinary single-phase working, while a subsidiary armature winding furnishes magnetizing current for the motors. The general arrangement of the armature coils is shown in Fig. 86. The winding in the small intermediate slots is of the same size of wire as the main coil, but has only one-fourth as many turns, and consequently one-quarter the main E. M. F. This so-called "teaser" E. M. F. is obviously 90° in phase from the main E. M. F. The relation of the two E. M. Fs. is better shown in Fig. 87, where *A B C* is the main E. M. F. and *B D* the teaser E. M. F. The generator has three collecting rings, of which the middle one is connected to *D*. The outer rings have the full E. M. F. between them, while between *D* and *C* the E. M. F. is the geometrical sum of *B C* and *B D*, approximately .56 of the main E. M. F. For motor

service the resultant E. M. Fs. differing in phase may be variously combined, usually into approximately three-phase relation, although in normal running all the *currents* in the motor are in very nearly the same phase. The object of this system

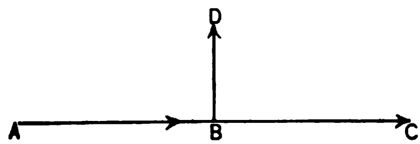


FIG. 87.

is to obtain for lighting purposes a perfectly simple circuit, the voltage of which will be quite undisturbed by actions going on in the subsidiary motor circuit, which object is attained if

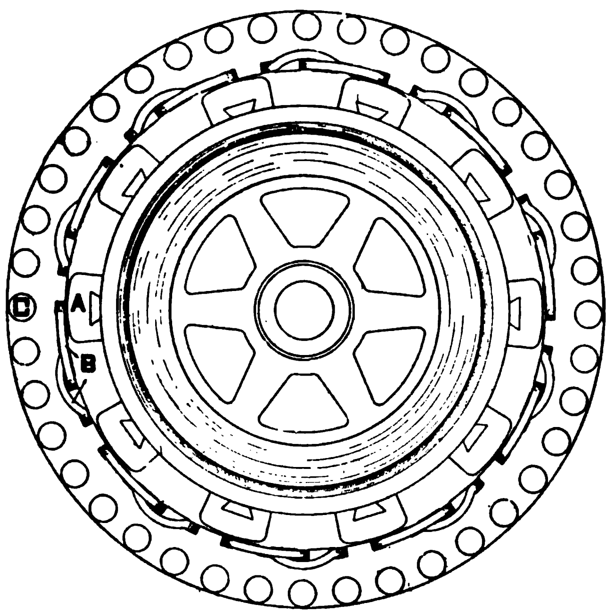


FIG. 88.

the generator is so arranged as to hold its voltage closely under inductive load.

A similar device for simplifying the operation of lighting circuits is a three-phase system arranged to supply the entire

lighting service from two of its lines, as *A* and *B*, Fig. 85. The other two connections *B C* and *A C* would only be used for motor service, and if desirable the coils *b* and *c* could take up very little space on the armature. Still another of these heterophasal schemes employs regular single-phase alternators for the lighting work, and a small adjunct machine in phase 90° from the others, and connected with them to form a two-phase circuit with one common wire. This connection is used for starting ordinary two-phase motors.

In general the heterophasal systems have no considerable advantage over the ordinary polyphase systems, save for a few special cases. In the chapter on centres of distribution the working properties of various alternating systems will be taken up in more detail.

In general construction and arrangement of parts all alternators are similar. Those specially intended for power transmission are sometimes, however, modified for convenience in obtaining high voltage or for direct coupling to water wheels. The vertical shaft arrangement as exemplified in the Niagara machines is now and then used both in this country and abroad. Machines for 3,000 to 5,000 volts and upward are best constructed with stationary armatures, to avoid mechanical strains on the high voltage insulation. In following this design the armature is usually exterior to the field magnets. It is very doubtful whether the fly-wheel effect gained by revolving an exterior magnet compensates for the great inaccessibility of the high voltage armature. A good example of the stationary armature construction is the Stanley two-phaser, shown in Figs. 88 and 89. The end view of the machine is shown in Fig. 88. There are two rings of laminated iron placed side by side, and connected by the iron keeper bars *C*. On the interior face of each ring is a two-phase winding *B*, similar to that shown in Fig. 75.

In front of these coils revolves the interior field magnet, of which a pole-piece is shown at *A*. This magnet structure is duplex, like the armature, carrying two crowns of laminated poles. Between these and supported by the armature structure is the field coil *A*, Fig. 89, inside of which the field magnet revolves. The relation of the parts is shown in Fig. 89. Obviously all the poles at one end of the machine are north

poles, those at the other end south poles, so that both sides of the armature are required to complete the magnetic structure. As these poles revolve they increase and decrease the magnetic induction through the armature coils *B*. Machines of this magnetic character are known as "inductor" dynamos.

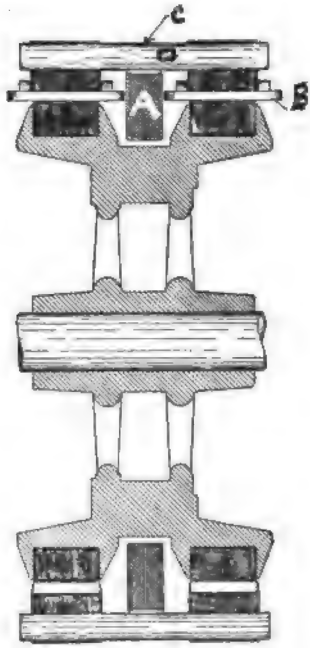


FIG. 89.

The example shown has upon it no moving wire whatever, and is admirably adapted for high voltage work.

Another form of internal magnet alternator considerably used abroad is shown in Fig. 90. It is an ordinary single-phase machine, with the revolving magnet poles alternately north and south. The exciting current is led in through two collecting rings, a proceeding which adds little to the complication and is quite unobjectionable. A similar form is occasionally used in this country.

Stationary armature machines are usually not compounded, although it is perfectly possible to do so if necessary, by a commutator on the magnet shaft.

Two- and three-phase machines may or may not be compound wound. When compounded, it is accomplished by the same sort of commutating device shown in Fig. 73, except that it is generally arranged to take the current for commutation from the several phase windings in succession.

As a matter of fact, in much power transmission work compound winding is not necessary, since the machines hold their

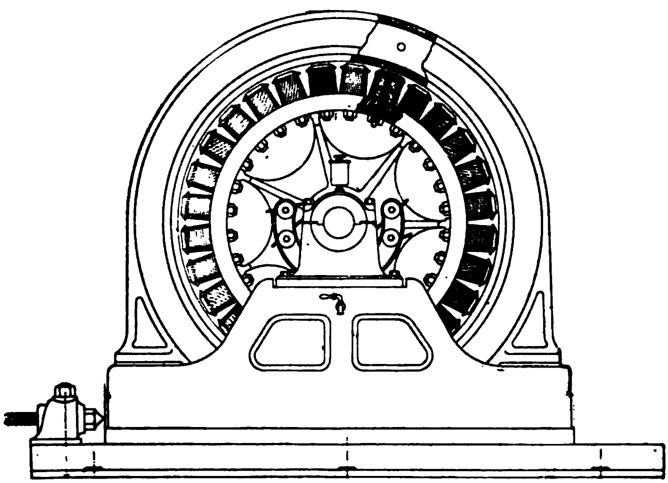


FIG. 90.

voltage closely without it if well designed, and in large plants the variations of load are often so gradual that the voltage at the end of the transmission line can be easily kept constant by hand regulation. Again, in many transmission plants several lines are fed by one generator, so that no compounding would suit all the lines; and whenever a sub-station is installed, the secondary voltage has to be kept constant by special regulation in any event.

TRANSFORMERS.

The alternating current transformer is merely a glorification, as it were, of the fundamental idea shown in Fig. 4, p. 12. The loops *A* and *B* are expanded into massive coils and are given a very perfect magnetic core of laminated iron, but the principle is unchanged.

In Fig. 91, *A* is a core composed of soft iron plates perhaps $\frac{1}{100}$ inch thick, stamped into the form shown, and then built up together like the leaves of a book, *B* is a coil of insulated wire wound in a spiral around one side of the core, and *C* is a single loop of heavy insulated copper bar around the other side. Now suppose an E. M. F. is suddenly applied to the terminals of the coil *B*, the loop *C* being left open. Current will flow through *B* in amount determined by its resistance and inductance, setting up a magnetic field throughout the mass of *A*. If the current is an alternating one an alternating magnetic

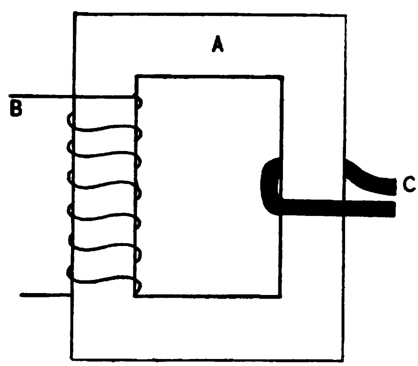


FIG. 91.

field will be set up in *A*, and the current in *B* will settle down to that value which is determined by the resistance and inductance of the coil. The energy represented by this current is spent in heating the coil and in doing work by the reversal of magnetism in the core *A*. The current thus engaged lags behind its E. M. F. as in other cases of inductive circuit, the power factor being in ordinary cases from .6 to .7.

Now close the loop *C*. Current opposing the current in *B* will be at once set up. The magnetizing effect of this reverse current opposes the magnetization due to *B*, and hence tends to cut down the inductance imposed on *B*, which is, as we have already seen, determined by the magnetic induction through its core. To this action *B* simultaneously responds with an increased current, so that any increase of the current in *C* and its consequent demagnetizing action, is automatically compensated by an increased current in *B*. The increase of energy

represented by this compensates for the energy due to the current in *C*. Energy is thus virtually transferred from the primary circuit *B* to the secondary circuit *C*.

Now as to the voltage of these two circuits. The energy in the two circuits is evidently equal save for losses in the iron and copper, which amount ordinarily to only a few per cent.

For any given magnetization in *A* the inductive E. M. F. in *B* is proportional to the total number of turns in the coil; so also the induced E. M. F. in the secondary is proportional to the number of turns in it. That is for a certain rate of change of the magnetic induction in *A*, the induced E. M. F. is the same *per turn* throughout *A*, whether that E. M. F. appears as inductance in *B* or secondary E. M. F. in *C*. Hence the E. M. Fs. across the terminals of the primary and secondary coils are proportional to the respective number of turns in those coils. But the energy in the two is substantially equal, and hence the currents in primary and secondary must be inversely proportional to the respective E. M. Fs. In Fig. 91 are shown seven primary turns and one secondary turn. Therefore the secondary E. M. F. is one-seventh the primary E. M. F., and the primary current is one-seventh the secondary current. For the same density of current in amperes per square inch the secondary turn must have seven times the cross-section of the primary conductor. By simply changing the relative number of primary and secondary turns,—the *ratio of transformation*,—electrical energy at any voltage can be transformed to any other voltage with trifling loss if the apparatus be properly constituted.

The losses which exist are of three kinds. First is the loss due to the resistance of the copper. This at light loads is very trifling, but increases with the square of the load, being numerically equal in watts to C^2R, as in all cases of loss through resistance.

Second comes the loss through *hysteresis*—virtually magnetic friction—produced by the alternate reversals of magnetization in the iron core. This is nearly constant at all loads and is kept as low as possible by securing the best possible iron, and working it at rather low magnetization, since the hysteretic loss increases very rapidly as the iron is more and more strongly magnetized.

Finally comes the loss from eddy currents in the core. This is due to the fact that the core is a fairly good conductor, and currents are induced in it for precisely the same reason that they are induced in the secondary winding. These eddy currents are largely reduced by carefully laminating the core across the natural direction of flow of these currents, and insulating the laminæ with sheets of tissue paper or with varnish. The loss from eddy currents is, generally speaking, of about the same magnitude as the hysteretic loss, and in transformer practice the two are usually lumped together and denominated core loss.

By careful construction and design these losses can be kept very small compared with the total output. The following data from a test of a 7,500 watt transformer designed for a frequency of 15,000 to 16,000 alternations per minute, about 125 to 135~, will give a clear idea of the results that can be reached commercially:

Output,	7.5 KW
Transformation ratio,	20 : 1
Full load amperes (primary),	3.6
Full load amperes (secondary),	72.0
Resistance (primary) ohms,	6.15
Resistance (secondary) ohms,	.012
Total $C^2 R$ loss (watts),	143.
Total core loss (watts),	78.
Primary current (no load),	.063
Power factor (no load),	.595
Total C R drop (per cent.),	1.9

The efficiency curve of this transformer at various loads is given in Fig. 92. The interesting feature of this curve is the very uniform efficiency from half load to full load, with a maximum of 97.4 per cent. at three-quarters load. This is the result of a relatively very small core loss. Even at one-tenth the normal load the efficiency is still good, over 90 per cent., although the curve falls more rapidly below half load.

Still larger transformers, such as are used for heavy power transmission work, are even more efficient than the one here described, although the room for increase is very limited indeed. Within the last few years the improvement in commercial transformers has been very great. In practice they

are seldom so simple in form as in Fig. 91, the core plates being universally built up of several pieces, so that the coils may be wound in forms and slipped into their respective places on the core. One of the forms which has been widely used is shown removed from its case in Fig. 93. The hollow

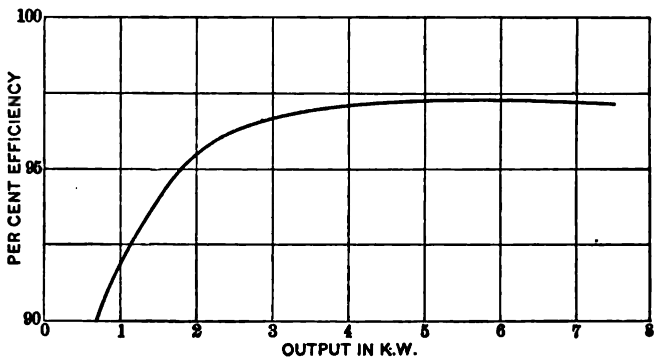


FIG. 92.

rectangle *A* forms the main part of the core, while the bridge piece, *B*, is built up separately as the core of the coils, together with which it is forced into the position shown. The secondary coil immediately surrounds the bridge, and

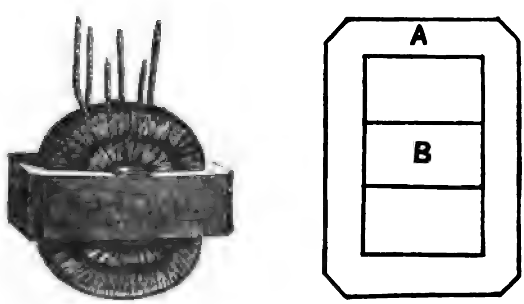


FIG. 93.

outside of it is the primary coil. Both coils are of course elaborately insulated.

As transformers are usually enclosed in tight iron boxes to protect them from the weather, the heat generated in the coils and core has a rather poor chance to escape, and the tempera-

ture may therefore rise higher than is safe for the insulation. It is usual to take special precautions to prevent this overheating. One of the commonest and best devices for this purpose is the subdivision of the core into bunches of laminæ separated by air spaces.

This arrangement is well shown in Fig. 94, in which the core is provided with a dozen of these ventilating spaces. The arrangement of the coils is somewhat like that of Fig. 93. As an additional precaution against overheating, the transformer case is often filled with heavy mineral oil after the core is in place. This both provides additional insulation,

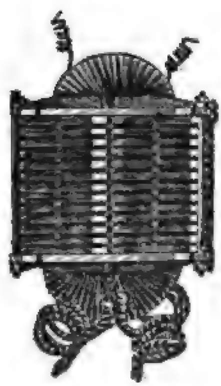


FIG. 94.

and facilitates the transfer of heat from the core and coils to the iron case, whence it is radiated to the surrounding air. In very large transformers the primary and secondary windings are often built up of thin flat sections assembled with spaces between them.

For huge transformers such as are used for sub-station work, means are generally provided for artificial cooling. Two methods are at present in use for this purpose. One is the use of a blast of air from a small blower streaming through the interstices provided in core and coils, and rapidly carrying away the heat generated. The other is applied to oil-filled transformers, and consists in cooling the oil by a worm in the transformer case through which cold water is allowed to flow, or with a small pump circulating the oil itself slowly

through a worm cooled by water. Either plan is very effective, and both are extensively used.

With properly designed transformers there is no difficulty in dealing with any voltage now in use, without the device of connecting transformers in series, which was formerly often employed for high voltage. If transformers are of similar size and design, they can be run in parallel with the utmost facility, and may very often be thus "banked" most advantageously, as with such connection it is easy to proportion the number of transformers in use to the load, so that they

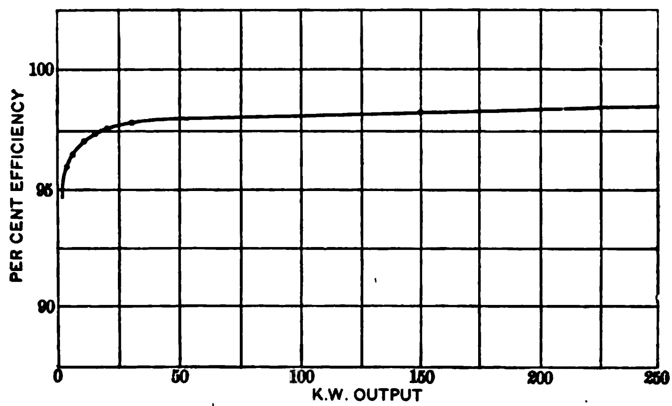


FIG. 95.

can be worked nearly at full load, and consequently at their best efficiency.

In general the larger the transformer the higher its efficiency, though the improvement is very slow after the output reaches 25 KW or thereabouts. The curve of Fig. 95 shows the change in full load efficiency with the size of transformer as found in the best American practice.

The data here given relate to transformers of the kind employed for power transmission work, as now produced by the best makers. The sizes of 50 KW and above are usually artificially cooled. The frequency is taken at 60~ to 70~, and the figures do not apply to transformers originally designed for higher frequencies. At lower frequencies the efficiencies are likely to be a fraction of a per cent. lower, but

at any frequency within the range of ordinary working a first-class transformer of 50 KW capacity or upward can be depended on for a full load efficiency of just about 98 per cent., and a half load efficiency about one per cent. lower. With care in planning a sub-station equipped with these large transformers the loss under normal conditions of working should not exceed 2½ per cent.

For polyphase work it is the almost universal custom in this country to employ simply groups of ordinary standard transformers. Abroad composite transformers, transforming two or more phases in a single structure, are often used. The intent of this arrangement is to utilize more fully the iron

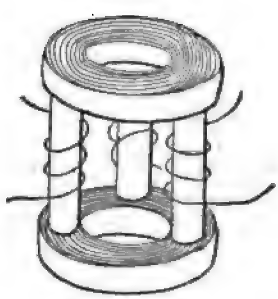


FIG. 96.

core by making it common to the several phase windings. Fig. 96 shows in rudimentary form the application of this principle to a three-phase circuit. Three laminated cores, with the laminæ running vertically, are united at the ends by lanimated yokes somewhat in the manner shown. Each core receives the primary and secondary windings belonging to a single phase, while the iron belongs to the three in common. The arrangement is akin to the mesh connection of three-phase circuits. Fig. 97 shows the form actually taken by a small three-phase transformer built up in this manner. It is a very neat and compact structure and certainly convenient for small work. In this country it is found that with American costs of labor, the saving due to a common use of core iron is more than counterbalanced by the extra work of building up the composite structure, besides which the distribution of

the iron in three cores is somewhat less advantageous in itself than the concentration of each core about its own coils.

Several arrangements of transformers are employed in poly-

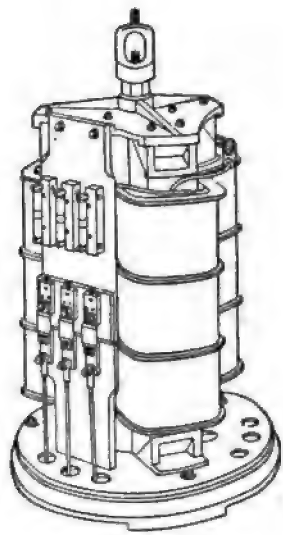


FIG. 97.

phase working corresponding to the various arrangements of polyphase circuits. For example, in two-phase systems the

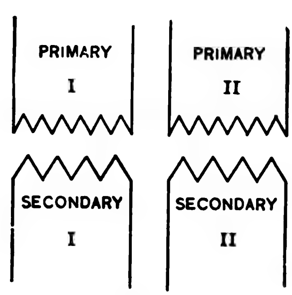


FIG. 98.

transformers are generally connected as shown in Fig. 98. This is simply one transformer per phase connected in the ordinary manner. The two phases are kept distinct both as regards

primary and secondary sides of the circuit. Fig. 99 shows the composite circuit method of connection. Both primary and secondary circuits have one wire common to both phases. In this case there is between the outside wires of the system a higher voltage than exists between either outside wire and the common wire. This voltage is of course the geometrical sum of the two separate phase-voltages. As these are 90° apart the resultant voltage is $\sqrt{2}$ times either component. Not infrequently the primary arrangement of Fig. 98 is combined with the secondary circuit of Fig. 99. This is the ordinary connection of two-phase motors, which are often built for

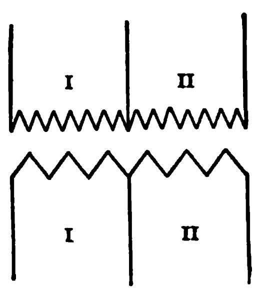


FIG. 99.

this three-wire circuit. As a rule all lighting connections and all long circuits of any kind are made as shown in Fig. 98.

Transformers for three-phase circuits, are, like the circuits themselves, very seldom worked with the phases separated, but in nearly every case are combined in the star or mesh connection. The former is useful in dealing with very high voltages, since the individual transformers do not have to carry the full voltage between lines. Fig. 100 shows a diagram of the star connection and Fig. 101 the corresponding mesh. In each *a*, *b*, *c*, are the primary leads, and *A*, *B*, *C* the corresponding secondary leads. Of the two connections the mesh is rather the more in use except for high voltage work, and for secondary distribution with a connection to the common junction of the transformer system, which connection has for certain purposes very great advantages.

Whether the star or the mesh connection is employed, one transformer per phase is required, and this condition is some-

times inconvenient as rendering necessary the use of three small transformers where a two-phase system would need but two. To obviate this difficulty, what may be called the

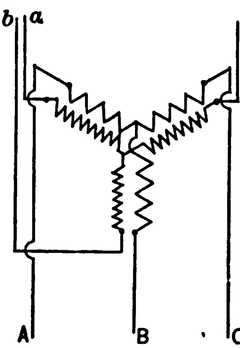


FIG. 100.

"resultant mesh" connection is extensively used, particularly for motors. The principles on which this is based have already been set forth.

Briefly, if one takes the geometrical sum of two E. M. Fs. not in phase with each other, the resultant will be less than the

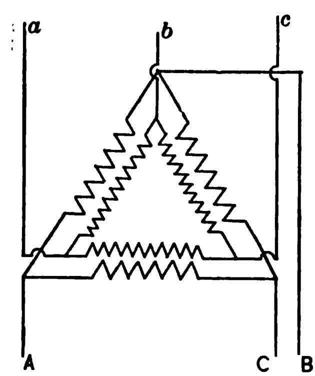


FIG. 101.

arithmetical sum of the components, and not in phase with either. From the examples of geometrical summation already discussed, it is evident that by varying the magnitudes of the components and the angle between them, *i. e.*, their phase

difference, the resultant may have any desired value and any direction with reference to either component.

The "resultant mesh" three-phase connection is shown in Fig. 102. It is composed of two transformers instead of three as in Fig. 101, the E. M. F. between the points *A* and *C* being the resultant derived from the two existing secondaries. Each of these secondaries contributes its part of the output in the resultant phase, and the secondary circuit behaves substantially as if it were derived from the ordinary mesh connection. This arrangement is very convenient in motor work, since it is very simple and allows the use of two transformers when desirable for the required output. Sometimes a motor is of a size that is fitted better by three standard

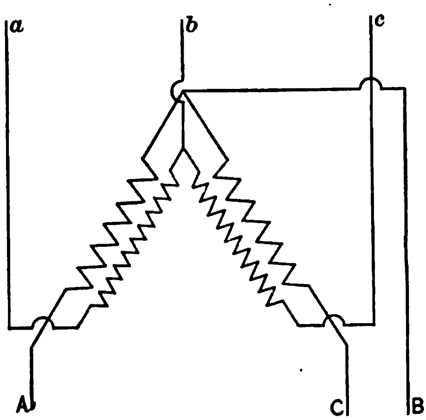


FIG. 102.

transformers than by two, or the reverse, and with the choice of the two mesh connections it is often possible to avoid some extra expense or to utilize transformers that are on hand.

A very beautiful application of this principle of resultant E. M. F. is the change of a two-phase system into a three-phase, or *vice versa*. The method of doing this is shown in Fig. 103. Suppose we have two equal E. M. Fs. 90° apart, as in the ordinary two-phase system, as the primary circuit. The secondary E. M. Fs. will still be 90° apart, but can be of any magnitude we please. Let one of these secondaries *A C* give say 100 volts, and tap it in the middle so that the halves, *A D*

and $D\ C$ will each be 50 volts; now wind the other secondary, $B\ D$ for $50\sqrt{3}$ volts, and connect one end of it to the middle point of the first secondary. Taking now the geometrical sums of $B\ D$ with the two halves of $A\ C$, the resultants are

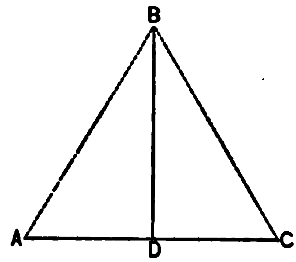


FIG. 103.

equal to each other and to $A\ C$, and leads connected to A, B, and C will give three equal E. M. Fs. 120° apart, forming a three-phase mesh with two resultant E. M. Fs. instead of one, as in Fig. 102. The actual connection of a 1,000 volt two-phase

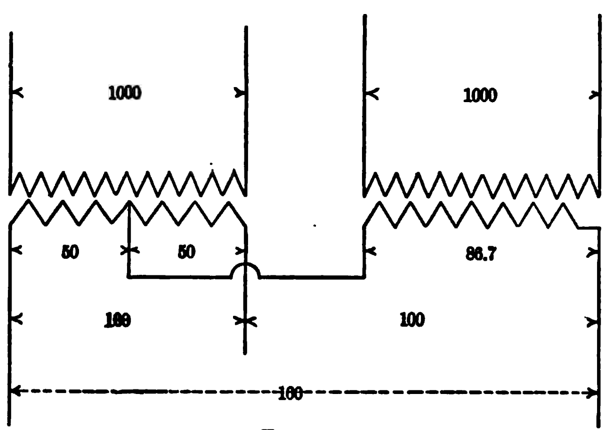


FIG. 104.

system to form a 100-volt three-phase secondary system is shown in Fig. 104. Reversing the operation by supplying three-phase current to the three-phase side of the system gives a resultant two-phase circuit.

This change-over process is valuable in that it allows a three-phase transmission circuit to be used for the saving in copper characteristic of it, in connection with two-phase generating and distributing plants, and permits two-phase and three-phase apparatus to be used interchangeably on the same circuit, which is sometimes advantageous. A somewhat analogous arrangement permits the transformation of a monocyclic primary circuit into a three-phase or two-phase secondary form, as may be convenient, and in fact any system with two or more phases may be transformed into any other similar system in the general manner described.

All these systems which involve resultant E. M. Fs. are open to certain practical objections which may or may not be important according to circumstances.

In the first place, the resultant E. M. F. is less than the sum of the E. M. Fs. for which the transformers in the component circuits are wound. For instance, in Figs. 102 and 104, 100 resultant volts are derived from transformers aggregating respectively 200 and 186.7 volts, through the secondaries of which the resultant current has to flow. In the former case one-third and in the latter case two-thirds of the total current is thus derived at a disadvantage, using up more transformer capacity for a given amount of energy than if the transformers were used in the normal manner. On a small scale the disadvantage is seldom felt, but in heavy transmission work with large transformers it may be quite perceptible.

Second, the disturbance of any one component voltage from drop or inductance, or any shifting of phase between the components from unequal lag, disturbs all the resultant E. M. Fs. This, again, may or may not be of importance, but it must always be borne in mind, as in every case of combined phases.

It is possible by combinations of transformers similar to those described, to obtain at some sacrifice in transformer capacity a single-phase resultant E. M. F. from polyphase components, or to split up a single-phase current, by the aid of inductance and capacity, into polyphase currents. Neither process is employed commercially as yet, since both encounter in aggravated form the difficulties common to resultant phase working mentioned above, and others due to the special form of the combinations attempted.

SYNCHRONOUS MOTORS AND MOTOR PRACTICE.

The principles of the synchronous alternating motor are a snare for the unwary student of alternating current working, since they involve, when discussed in the usual way, rather complicated mathematical considerations. And the worst of it is that the generalized treatment of the subject often causes one to lose sight of the fundamental ideas that are at the root of alternating and continuous current motors alike. The subject is at best not very simple, and unless we are prepared to attack the general theory with all its many considerations, it is desirable not to cut loose from the common basis of all motor work.

Recurring to the rudimentary facts set forth in Chapter I, we see that an electric motor consists essentially of two working parts—a magnetic field and a movable wire carrying an electric current. The motive-power—torque—is due to the reaction between the magnetic stresses set up by the current and those due to the field. The refinements of motor design are concerned with the efficient production of these two sets of stresses and their co-ordination in such wise that their reaction shall produce a powerful torque in a uniform direction.

In continuous current motors, for example, the field magnets are energized by a part or the whole of the working-current, and this current is passed, before entering the armature, through a commutator like that of the generator, so that in the armature the direction of the currents through the working conductors shall be reversed at the proper time, so as to react in a uniform direction with field poles which are consecutively of opposite polarity. Were it not for the commutator the armature would, on turning on the current, stick fast in one position, as may happen when there is a defect in the winding.

Now, since the function of the commutator in the generator is to change a current normally alternating, so that it shall flow continuously in one direction, and since the object of the commutator in the motor is periodically to reverse this current in the armature coils, thus getting back to the original current again, one naturally asks the reason for going to all this trouble. Why not let the generator armature do the revers-

ing instead of providing two commutators—the second to undo the work of the first?

The reason is not far to seek. In a generator running at uniform speed the reversals of current take place at certain fixed times—whenever an armature coil passes from pole to pole, quite irrespective of the needs of the motor. The commutator on the other hand reverses the current in the motor armature coils in certain fixed positions with respect to the field poles so as to produce a continuous pull, irrespective of what the generator is doing.

If we abolish the commutators the motor will run properly only when the alternating impulses received from the generator catch the armature coils systematically in the same positions in which reversal would be accomplished by the commutator. Hence for a fixed speed of the generator the impulses will be properly timed only when the motor armature is turning at such a speed that each coil passes its proper reversal point simultaneously with each reversal of the generator current. If generator and motor have the same number of poles, this condition will be fulfilled only when they are running at exactly the same number of revolutions per minute. In any case they must run synchronously *pole for pole*, so that if the motor has twice as many poles as the generator, it will be in synchronism at half the speed in revolutions per minute, and so on.

If we try to dispense with the commutators when starting the motor from rest, the action will obviously be as follows: The first impulse from the generator might be in either direction, according to the moment at which the switch was thrown. The reaction between this current in the armature coils and the field poles might tend to pull the armature in either direction, but long before the torque could overcome the inertia of the armature a reverse impulse would come from the generator and undo the work of the first. Consequently the motor would fail to start at all.

If the impulses from the generator came very slowly indeed, so that the first could give the armature a start before the second came, the armature would stand a chance of getting somewhere near its proper reversal point before the arrival of the reverse current, and thus might get a helping pull that

would improve matters at the next reversal, but the direction of the first impulse would be quite fortuitous. Starting the armature in either direction before the current is thrown on gives it a better chance to go ahead if the first impulses in the wrong direction are not strong enough to stop it altogether.

We see, then, that an alternating current derived from the generator direct does not give reversals in the motor coils that are equivalent to the action of a commutator, save at synchronous speed. Except at this speed the current from the generator does not reverse in the motor armature coils when the latter are in the proper position.

Fig. 105 will give a clear idea of the condition of affairs in the field and armature conductors of a continuous current motor. Here *S* and *N* are the poles, and + and — mark the

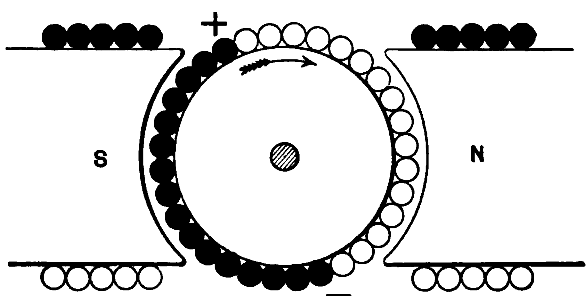


FIG. 105.

positions of the positive and negative brushes with reference to the armature winding. The solid black conductors carry current flowing down into the plane of the paper. The white conductors carry current upward. The armature turns in the direction of the arrow, and as each conductor passes under the brush the current in it is reversed. This distribution of current is necessary to the proper operation of the motor, and if the brushes are moved the motor will run more and more weakly, and then stop and begin to run in the opposite direction, until when the brushes have moved 180° the motor will be running at full power in the reverse direction. This final position means that the currents in the two halves of the armature have exchanged directions, so that the conductors originally attracted toward *N* and repelled from *S*, are now

repelled from *N* and attracted toward *S*. If alternating current from the generator is led into the windings, the distribution of current shown in Fig. 105 must be preserved, and since in abolishing the commutator the alternating current leads are permanently connected to two opposite armature coils through slip rings, the distribution of Fig. 105 can only be preserved when these leads change places by making a half revolution every time the current reverses its direction. Otherwise the distribution of currents will be changed, and the motor will fail to operate, since each reversal of current will catch the armature in a wrong position, and may tend to turn it in the wrong direction as much as in the right.

Hence such a motor must run in synchronism, or not at all,

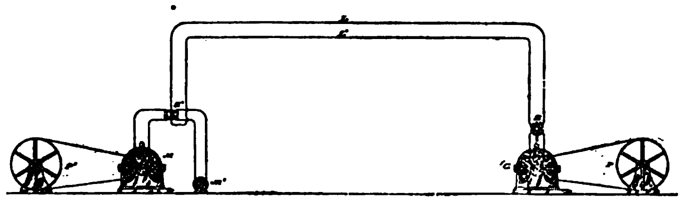


FIG. 106.

and to operate properly it must either be brought to full synchronous speed before the alternating current is turned on, or nursed into action by running the generator very slowly, working the motor into synchronous running at very low speed, and then gradually speeding up the generator, thus slowly pulling the motor up to full speed. In practice the former method is uniformly employed, and the machine used as a synchronous motor is substantially a duplicate of the alternating generator as already described. In fact, it is an alternating generator worked as a motor, just as a continuous current motor is the same thing as the corresponding generator.

Fig. 106 gives a clear idea of the way in which synchronous alternating motors are employed for power transmission. Here *G* is the generator driven from the pulley *P*. *S* is a switch connecting the generator to the line wires *L L'*. At the motor end of the line is a second switch *S'*, which can connect the line either with the synchronous motor *M*, or the starting motor *M'*. This latter is usually some form of self-starting

alternating motor to which current is first applied. M' then gradually brings M up to synchronous speed; when the switch S' is thrown over, the main current is turned on M, and then the load is thrown on the driving pulley P' by a friction clutch or some similar device.

Such a system has certain very interesting and valuable properties. We can perhaps best comprehended them by comparing them with the properties of continuous current motor systems.

In the alternating system both generator and motor are usually separately excited, which means really that the field strengths are nearly constant; as constant in fact as those in a well designed shunt-wound generator and motor for continuous current.

Now we have seen that this latter system is beautifully self-regulating. Whatever the load on the motor, the speed is nearly constant, and the current is closely proportional to the load. If the load increases, the speed falls off just the minute amount necessary to lower the counter E. M. F. enough to let through sufficient current to handle the new load. The effective E. M. F. is the difference between E, the impressed E. M. F. and E', the counter E. M. F. The current produced by this E. M. F. is determined by Ohm's law.

$$C = \frac{E - E'}{r} \qquad (1)$$

where r is the armature resistance, and since we have seen that the output of the motor is measured by the counter E. M. F.,

$$W = C E' \qquad (2)$$

where W, in watts, includes frictional and other work. E', neglecting armature reaction, is proportional to the speed of the armature, which falls under load just enough to satisfy equation (2) by letting through the necessary current.

Now we have seen that when we abandon the commutator the motor has to run at true synchronous speed, or else lose its grip entirely. How can it adjust itself to changing conditions of load? If the load increases, more current is demanded to keep up the output, but the field strength remains constant, and the counter E. M. F. of the motor cannot fall by reduction of speed. We must note that while in a continuous-current motor the

counter E. M. F. of the armature is constant at uniform speed, in an alternating motor the counter E. M. F. varies like that of the generator, following approximately a sinusoidal curve, as the position of the armature with respect to the field poles varies.

Hence at any given instant the counter E. M. F., the speed and field strength remaining the same, depends on the position of the motor armature. In Fig. 107 we have a pair of alternating machines, generator *A* and motor *B*. In normal running

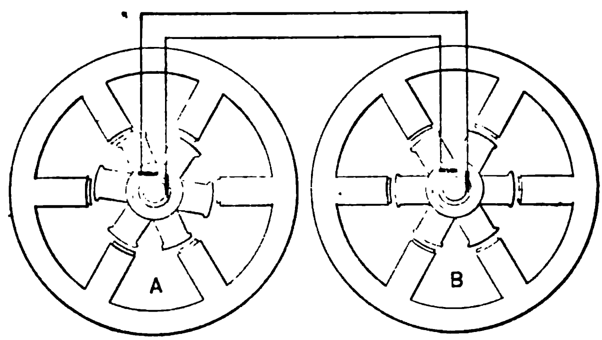


FIG. 107.

at light load, the two are nearly in opposite phase, since of course the impressed and counter E. M. Fs. are virtually in opposition.

Now, if there is an increase of load the motor armature sags backward a little under the strain, thereby lessening the component of its counter E. M. F. that is in opposition to the impressed E. M. F. The current increases, and with it the torque, and the sagging process stops when the torque is great enough to carry the new load at synchronous speed. The change of phase in the counter E. M. F. thus takes the place of change of absolute speed in the continuous current motor, by the same general process of increasing the E. M. F. effective in forcing current through the circuit. This effective E. M. F. is generally by no means in phase with the impressed E. M. F., and in general the current and the impressed E. M. F. are not in phase in a synchronous motor. Here, as elsewhere, the input of energy is

$$C\,E \cos \varphi,$$

while the output, which in the continuous current motor is

simply the product of the current and the counter E. M. F., in the synchronous motor depends evidently on such parts of both as are in phase with each other, *i. e.*,

$$W = C\,E'\cos\varphi' \qquad (3),$$

in which φ' is the angle between current and counter E. M. F. Likewise the current, which in the continuous current motor depends on the effective E. M. F. and the resistance, now depends on the counter E. M. F. and the impedance I. So that

$$C = \frac{E - E'}{I} \qquad (4).$$

In this equation the values of all the quantities depend on their relative directions, and by combining geometrically the

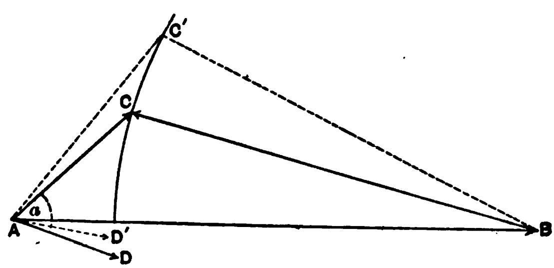


FIG. 108.

factors of (4) we can form a clear idea of the singular relations that may be found in synchronous motor practice.

The construction is similar to that found in Fig. 47, p. 119.

In Fig. 108, we will start with an assumed impressed E. M. F. of 1000 volts, a counter E. M. F. of 800 volts and an impedance composed of 5 ohms resistance and 10 ohms equivalent inductance.

To begin with, we will lay off the impressed E. M. F. $A\,B$, and then the counter E. M. F. $B\,C$, which as we have seen is in partial opposition to $A\,B$. In this case $A\,C$ is the resultant E. M. F., which, on the scale taken, is 300 volts. This, then, is the available E. M. F. taken up by the inductive and ohmic drops in the armature. The next step is to find C (eq. 4) from I, and the value of $E - E'$, just obtained. To obtain I, we must combine resistance and inductance, as shown in Fig. 109. Performing this operation, it appears that $I = 11.18$. Hence in the case in hand $C = \frac{300}{11.18} = 26.8+$ amperes. As to the

direction of this current, we know that it is at right angles to the inductive E. M. F, *i. e.*, is in phase with the resistance in Fig. 109. Solving that triangle to obtain the angle between the current and impedance, it turns out to be a little over 63°, being the angle whose tangent is $\frac{10}{5}$. Laying off this angle *a* from *A C*, the impedance in Fig. 108, we find the current to be in the direction *A D*. This current then is out of phase with the impressed E. M. F. by the angle of lag *D A B*. It is also out of phase with the counter E. M. F., though by chance very

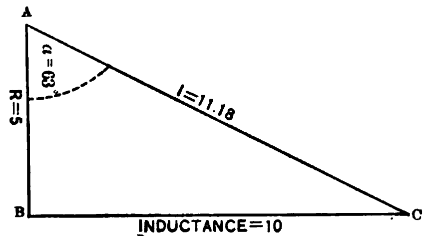


FIG. 109.

slightly, and lags behind the resultant E. M. F. *A C*, by the angle *a*. Being nearly in phase with the counter E. M. F., the gross output of the motor is approximately $26.8 \times 800 = 21.4$ KW.

Now, what happens when the load increases? The motor armature sags back a few degrees under the added torque, and the counter E. M. F. takes the new position *B C'*. The new resultant E. M. F. is *A C'*, which on the scale taken equals 450 volts. The new value of the current is $C = \frac{450}{11.18} = 40.25$ amperes, and its phase direction, 63° from *A C'*, is *A D'*. The new angle of lag is then *D' A B*, showing that under the larger load the power factor of the motor has improved. If *C B* should lag still more, *A C'*, together with the current, would keep on increasing. Evidently, too, the angle of lag *D' A B* will grow less and less until *A C' B* becomes a right angle, when in the case shown it will be very minute, and the power factor will be almost unity. Beyond this point the angle *C' A B* will obviously begin to decrease, and *D' A B* will begin to open out, again lowering the power factor at very heavy loads.

Hence it appears that at a given excitation there is a particular load for which the power factor is a maximum, and it is evident from the figure that in the example taken this maximum will be higher as the inductance of the system decreases, and also will pertain to a smaller output. Let us now see what happens when the excitation of the motor is varied. In Fig. 110 the conditions are the same as before, except that we assume counter E. M. Fs. of 500 volts corresponding to *C* and 1,100 volts corresponding to *C'*. Examining the former, the resultant E. M. F. is *A C* = 528 volts, the corresponding current is 47+ amperes and the angle of lag *D A B* is much greater than before. The power factor evidently would still

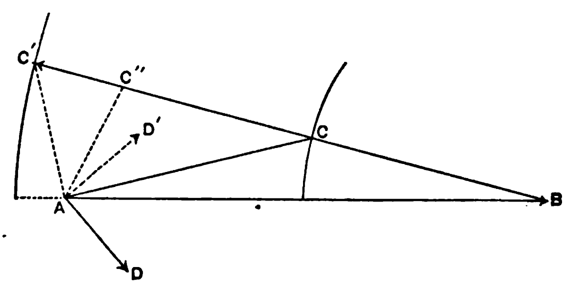


FIG. 110.

be rather bad under increased loads, and worse yet, when at lighter loads the angle *A B C* decreases. Lessened inductance, however, would help the power factor by decreasing the angle *C A D*, and hence *B A D*. Now, consider the result of increasing the motor excitation to *B C'* = 1,100 volts. The resultant E. M. F. now becomes *A C'*, being shifted forward nearly 90°, its value is 280 volts and the current is 25+ amperes. But this current is now in the direction *A D'*, *a* being the same as before, and hence it no longer lags, but *leads* the impressed E. M. F. by nearly 45°. The power factor is therefore still bad, but gets better instead of worse under loads greater than that shown. Inductance in the system now improves the power factor, and combined with heavy load might bring the current back into phase with the impressed E. M. F.

The counter E. M. Fs. corresponding to *C* and *C'* are

rather extreme cases for the assumed conditions, but it is easy to find a value for the excitation which would annull the lag exactly for a particular value of the load. Laying off in Fig. 110 $C'' A B = C' A D'$ we find the required counter E. M. F., which is very nearly 910 volts. At the particular output corresponding to this condition, the power factor is unity, the current and the impressed E. M. F. are in phase, and since the current is therefore a minimum for the output in question, the efficiency of the conducting system is a maximum.

Throughout this investigation it has been assumed that the ratio of resistance and inductance has been constant. This is not accurately true, but is approximately so when the inductance is fairly low. The phenomenon of leading current in a synchronous motor system does not indicate that the current, in some mysterious way, has been forced ahead of the E. M. F. which produces it, for the impressed E. M. F. is not responsible for the current, which is determined solely by the resultant E. M. F. behind which, in the absence of considerable capacity, the current invariably lags.

The net practical result of all this is that a synchronous alternating motor, under varying excitation, is capable of increasing, diminishing, or annulling the inductance of the system with which it is connected, or can even produce the same result as a condenser in causing the current to lead the impressed E. M. F. The maximum torque of the motor, which determines the maximum output, is determined by the greatest possible value of $C E' \cos \varphi'$ consistent with the given impedance and electromotive forces. The stronger the motor field, and the less the armature inductances and reactions of both generator and motor, the greater the ultimate load that can be reached without overburdening the motor and pulling it out of step.

As regards the relation in phase between current and impressed E. M. F., the three commonest cases are those for which the currents were computed for Figs. 109 and 110. The first, and commonly the most desirable, is that in which the current lags slightly at small loads, gradually lags less and less, comes into phase, or very nearly so, at about average load, and lags slightly again at heavy loads. The maximum efficiency of transmission, reached when the lag touches zero, is then at

about average load. The second and commoner case is when the motor is rather under-excited, so that the lag merely reaches a minimum, never touching zero. The third case is that in which the current leads at all moderate loads, passes through zero lag, and then lags more and more. The average power factor may be the same as in the first case, but more energy is required for excitation, and no advantage is gained except in carrying extreme loads, often undesirable on account of overheating, or in modifying the general lag factor.

It is highly desirable for economy in transmission that the product of current and E. M. F. should be a minimum for the required load. This condition can be fulfilled for the motor circuit at any load by changing the excitation until the current for that load becomes a minimum. Further, the field of a uniformly loaded motor may in the same way be made to bring the entire line current of the system to a minimum for any given load on the system. Thus a synchronous motor load can be made very useful in improving the general conditions of transmission. By changing the motor excitation as the load on the motor or the system varies, the power factor can be kept at or near unity for all working loads.

Fig. 111 shows the power factor of a synchronous motor somewhat under-excited, and that of a similar machine with a field strong enough to produce lead at moderate loads. With proper adjustment of its field, the effect of a synchronous motor on the general conditions of distribution is very beneficial. In curve *A*, Fig. 111, the indications are that the motor had rather a high inductance and armature reaction, and the excitation was decidedly too low for good results. Curve *B* is from a 300 HP motor, with its field adjusted for zero lag at about $\frac{5}{8}$ load. The inductance was low and the armature reaction small. The result is somewhat startling. Even at $\frac{1}{8}$ load the power factor (current leading) is about .93. At half load it has passed .99, touches unity, and then slowly diminishes to very nearly .98 (lagging) at full load. In this case the generator was held accurately at voltage while the excitation of the motor was uniform. Both were polyphase machines wound for 2,500 volts.

When a synchronous motor is used in this manner, it obviously will show, at the same load, values of the current varying

if the excitation be varied. For any load the minimum current is given by that excitation which brings the current into phase

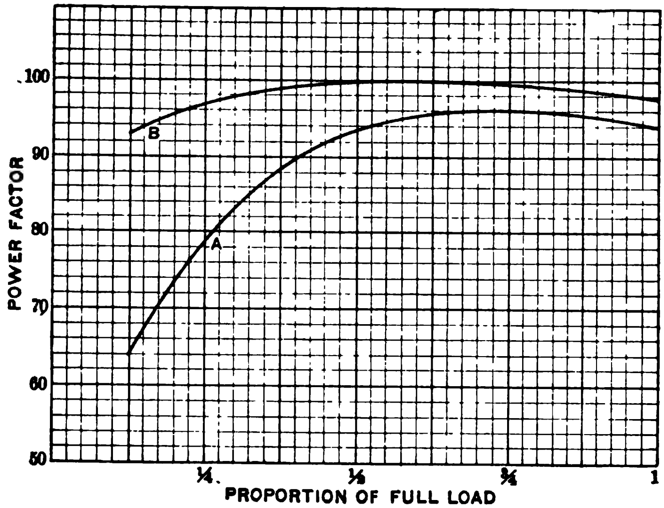


FIG. 111.

with the impressed E. M. F. This point is fairly well defined. At less excitation the current lags, with more it leads.

Fig. 112 shows for a particular instance the relations between the current and the excitation of the motor field, at full load of the motor. It is evidently easy to adjust the excitation to the proper point.

In the practical work of power transmission the synchronous motor has several salient advantages to commend it. At constant frequency it holds its speed absolutely, entirely independent of both load and voltage until, from excessive load or greatly diminished voltage, it falls out of phase and stops.

It constitutes a load that is substantially non-inductive, so that it causes no embarrassing inductive complications in the system, and takes current almost exactly in proportion to its work.

Finally it can be made to serve the same end as a condenser of gigantic capacity in compensating for inductances elsewhere in the system, and thus raising the general power factor substantially to unity.

As compensating disadvantages, it must run at one fixed uniform speed under all conditions, it is not self-starting, and it requires the constant use of a continuous-current exciter.

For many purposes the fixed speed is no objection, and in most large work the exciter can be used without inconvenience. Inability to start unaided, even when quite unloaded, is on the other hand a very serious matter, and has driven engineers to many ingenious subterfuges. The simplest of these is to pro-

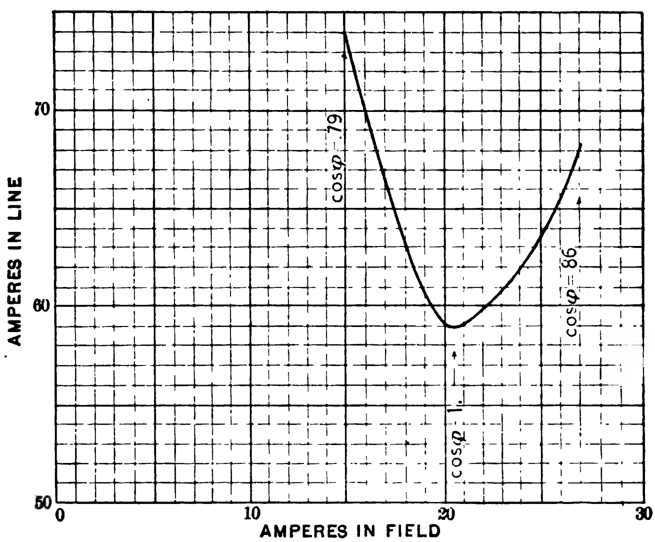


FIG. 112.

vide a starting motor, which is supplied with power by any convenient means, and serves to bring the main machine up to synchronous speed. Then the main current is thrown on, the motor falls into synchronism, and the load is taken up by means of a clutch. The difficulty is to start the starting motor. In transmissions of moderate length, continuous current may be delivered over the main line from the exciter of the generator to the exciter of the motor, which is thereby driven as a motor, and brings the alternating motor up to speed. As the energy required for this work is not great, say 10 per cent. of the whole power transmitted, it can

often be delivered quite easily. At long distances, however, the drop becomes too great for the moderate voltages available for continuous current, and other methods have to be used.

The best known of these is one used in several synchronous motor plants by the Westinghouse Company—notably in a large pioneer plant at Telluride, Col. This method is shown in Fig. 113. The main synchronous motor *S* is connected to its driving pulley *P* through the friction clutch *C*. On the motor shaft is a friction pulley *R*. The starting motor *M* is a Tesla induction motor, fitted to run on a single-phase circuit, and

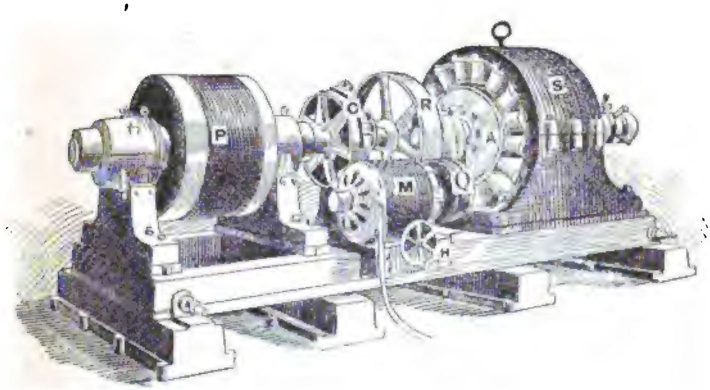


FIG. 113.

supplied with a friction pulley *Q*. *M* slides upon ways so that by turning the handle *H*, *Q* can be brought into contact with *R*.

In starting, current is first thrown upon *M*, bringing it up to speed. Then, the clutch *C* having been opened, *M* is moved until *Q* and *R* are in good contact, and rapidly brings *S* up to speed. The current is then thrown from *M* into the armature *A* of the large motor, the load is taken up by tightening the clutch *C*, and *M* is withdrawn to its original position. The process is quite simple and easy, and the apparatus works well.

Another method sometimes used is a special commutator to rectify the current applied to the main motor armature, thus directing the impulses so as to secure a small starting torque,

enough to bring the motor to speed. Then the commutator is abandoned and the motor falls to running synchronously.

An ingenious modification of this plan is found in the self-starting synchronous motor of the Fort Wayne Electric Corporation, shown in Fig. 114.

This machine has a double-wound armature. The main winding is of the kind usual in alternators, wound in slots in the armature core, and the leads belonging to it connect with

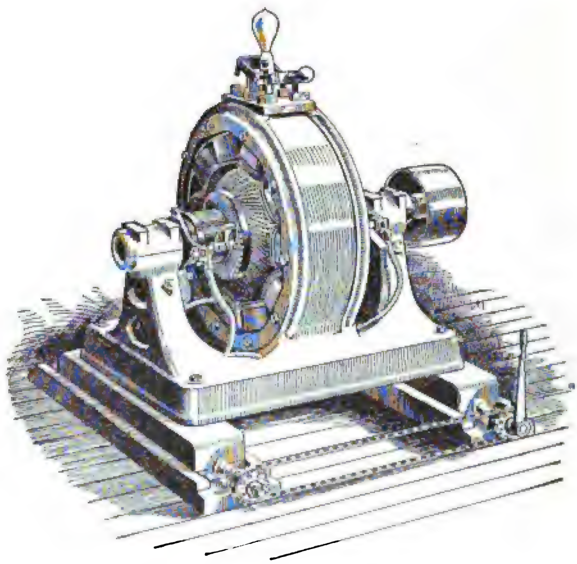


FIG. 114.

the collecting rings *via* the brushes on the pulley end of the shaft.

The other winding is a common continuous current drum-winding, laid uniformly on the exterior of the armature. It is provided with a regular commutator as shown in the figure.

The field is of laminated iron, and the field coils are in series with the continuous current winding.

Now, when alternating current is fed into a series-wound continuous current motor, the machine will start itself and run, for although the armature current reverses at all sorts of times with respect to the winding, the field also reverses simultane-

ously, so that the motor tends to run in the same direction, the relation between the currents in armature and field being quite unchanged by the reversal.

The motor in question is started by turning the alternating current, reduced to a moderate voltage by transformation, into the field and the commutated winding. The machine then starts with a good torque, and when it has reached synchronous speed, indicated by the pilot lamp on the top of the motor being thrown into circuit by a small centrifugal governor, a switch is thrown over, sending the main current through the alternating winding and closing the field circuit upon the commutator. The motor then runs synchronously, the excitation being furnished by the winding used for starting. This construction is best suited for rather small machines, as the double-winding is rather cumbersome for very large motors.

Except for inevitable sparking and rather high inductance, a series-wound commutating motor could be successfully used on alternating circuits. When used only for starting, little trouble is encountered from these causes.

At present the tendency in synchronous motor practice is toward the use of polyphase machines. These start well, when properly designed, as *induction* motors, which will be described later, and when at speed the field excitation is thrown on, and the machine thereafter runs in synchronism. Synchronous polyphase motors possess the same general properties as other synchronous motors, and as most power transmission work is now done by polyphase currents, they are widely used. The Telluride plant mentioned is now changed to biphase.

In general transmission work, synchronous motors find their most useful place in rather heavy work, which can be readily done at constant speed.

They have high power factors even when used for very varying loads, and are valuable in neutralizing inductance in the line and the rest of the load. Even when not deliberately used for this purpose, they raise the general power factor, and thus have a steadying effect that is very useful. When working under steady load and excited correctly, they almost eliminate the lagging current that sometimes becomes so great a nuisance in alternating current working.

The polyphase synchronous motors will run steadily even

if one of the leads be broken, working then as mono-phase machines, and by stiffening the excitation will generally carry their full normal loads without falling out of synchronism.

In one case that came to the author's notice, such an accident befell a three-phase synchronous motor, which went quietly on driving its load of 1,700 looms for four hours, until the mill shut down at night.

For small motor work synchronous machines are somewhat at a disadvantage, from the complication of the exciter and inability to start under load. In sizes below 100 HP they have been very generally superseded by the far simpler and more convenient induction motor, the use of which is a most characteristic feature of modern power transmission.

INDUCTION MOTORS.

An induction motor is a motor into which working current is introduced by electromagnetic induction instead of by brushes. It has therefore two distinct, although co-ordinated, functions—transformer and motor. To understand its action we must take care not to confuse these functions, and this is best done by recurring to the fundamental principles that are at the root of all motors of whatever kind.

An electric motor consists of these essential parts, viz.: A magnetic field, a movable system of wires carrying electric currents and means for organizing these two elements so as to produce continuous torque.

These parts are beautifully shown in their elementary simplicity in Barlow's wheel, Fig. 115, invented nearly three-quarters of a century ago.

In this machine *N S* is the permanent field-magnet, the arms of the star-shaped wheel are the current-carrying conductors, and a little trough placed between the magnet poles, and partly filled with mercury, serves with the wheel as a commutator. Its function is to shift the current from one conductor to the next following one, when the first passes out of an advantageous position. In other words it keeps the current flowing so as to produce a constant torque, irrespective of the movement of the conductors. Such is precisely the function of the modern commutator, and it is interesting to note

that the device of making the armature conductors themselves serve as the commutator is successfully used in some of the best modern machines.

These same fundamental parts are found alike in motors designed for continuous or for alternating currents. We have already seen that a series-wound motor can serve for use with both kinds of current, since the commutator distributes the current alike for both, and since the direction of the torque is determined by the relative direction of the main field and that

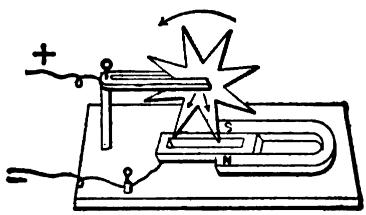


FIG. 115.

due to the moving conductors, alternations, which affect both symmetrically, leave the torque unchanged.

We have seen also that if the distribution of currents given by the commutator can be simulated by supplying the armature with alternating impulses timed as the commutator would time them, we can dispense with the commutator, and substitute two slip rings. In this case, however, the motor will only run when in synchronism, since only then will the alternating impulses from the generator be properly distributed in the armature, as has already been explained. Besides, the current has to be introduced into the armature through brushes bearing on a pair of slip rings, and an exciter is required to supply the field. If one could use an alternating field, and induce the currents in the armature as one would in the secondary of a common transformer, the machine would be of almost ideal simplicity.

This is what is accomplished in the induction motor. The field is supplied with alternating current, and the working current is induced directly in the armature conductors.

To this end the brushes used in the previous examples may be replaced by a pair of inducing poles, carrying the primary

windings, to which the armature windings play the rôle of secondary. These armature windings are therefore closed on themselves, instead of being brought out to slip rings.

For this short-circuited winding various forms are employed, the simplest being shown in Fig. 116. It consists of a set of copper bars thrust through holes near the periphery of the

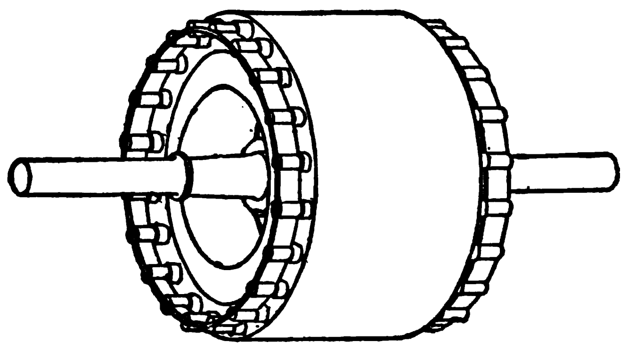


FIG. 116.

laminated armature core, and all connected together at each end by heavy copper rings.

The simplest arrangement of field and inducing poles is shown in Fig. 117. Here each pair of opposite poles is provided with a separate winding, so that the circuit *A A* supplies alternating current to one pair and *B B* to the other pair. The armature we will assume to be like Fig. 116. Now apply an alternating current to *A A*. The windings of the armature which enclose the varying electromagnetic stress will have set up in them a powerful alternating current almost 180° behind the primary current, *i. e*, in general opposed to it in direction, as considerations of energy require. The armature will not turn, however, for two very good reasons: first, the current in it is far out of phase with the magnetization of the poles; and second, this current is quite symmetrical with respect to the poles, so that the only effect could be a straight push or pull without the slightest tendency to attract or repel one side of the armature more than the other.

To produce rotation as a motor, there must be not only a

current in the armature conductors, but there must be field poles magnetized and disposed so as to produce a torque upon these conductors.

Suppose, now, an alternating current to be sent around the circuit *B B*. If it is applied simultaneously with the current in *A A*, we shall be no better off than before, for since the two pairs of poles act together and just alike, there is no magnetiza-

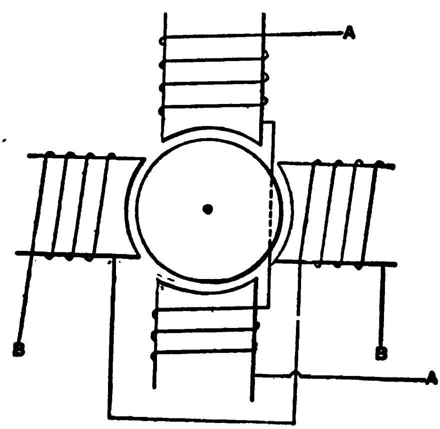


FIG. 117.

tion in phase with the armature current, and nothing to cause the armature to turn either way.

To obtain rotation we must arrange the two sets of poles so that one pair may furnish a magnetic field with which the current induced by the other pair is able to react. The simplest way of doing this is to supply *B B* with current 90° in phase behind the current in *A A*. Then when the current induced by *A A* rises, it finds the poles *B B* energized and ready to attract it, for the magnetization in *B B* and the current are less than 90° apart in phase. The less the lag of the armature current behind its E. M. F., the more nearly will the magnetization of these field poles be in phase with the armature current, and the more powerful will be the torque produced.

The *B B* set of poles necessarily induce secondary currents in the armature in their turn, toward which the *A A* poles serve

as field during the next alternation. The directions of both armature current and field magnetization are now reversed, so that, as in the commutating motor, the torque is unchanged. The next alternation begins the cycle over again, and so the motor runs up to speed. Its direction of rotation depends evidently upon the relative directions of magnetization in the two sets of poles, for these determine the direction of the armature current and the nature of the field poles that act upon it. Reversing the current in *A A* or *B B* will therefore reverse the motor, while reversing both will not.

The speed of the armature is determined in a rather interesting manner. When the armature is in rotation the electromagnetic stresses which act upon a given set of armature conductors are subject to variation from two causes. First is the variation in magnetization, due to changes in the primary current; second, the variation due to the armature coils moving as the armature turns, so as to include more or less of the magnetic stress. The E. M. F. in the armature conductors is due to the summed effect of these two variations. And since the two are in opposition, if the armature were moving fast enough to make a half revolution for each alternation of the field, the E. M. F. produced would be zero, since the rates of change in the field and in the area of stress included by the armature coils would be equal.

This means that the armature must always run at less than synchronous speed—enough less to produce a net armature E. M. F. high enough to give sufficient armature current for the torque needed.

Under varying loads, therefore, an induction motor behaves much like a shunt-wound continuous current motor. In both, the armature current is due to the net effect of an applied and a counter E. M. F., the former being delivered from the line through brushes in the one case and by induction in the other.

If the load increases, demanding an increased torque, the armature slows down a trifle, until the new armature E. M. F. and resulting current are just sufficient to meet the new conditions. In the continuous current motor this speed is determined by the resistance of the armature, to which the current corresponding to a given decrease of speed is necessarily pro-

portional. In the induction motor the armature *impedance* plays a precisely similar rôle. Fig. 118 shows the actual speed variation of a 100 HP induction motor in terms of its output. The maximum fall in speed under full load is a trifle less than 3 per cent., and even this result is sometimes surpassed in induction motors for especial purposes. A motor with higher armature impedance would fall more in speed, like a shunt motor with a rather high armature resistance. We thus see that the induction motor, as it should, behaves much like any other motor; the torque is produced in the same way; and obeys similar laws; the motor is similarly self-starting, and works on the same general principles throughout.

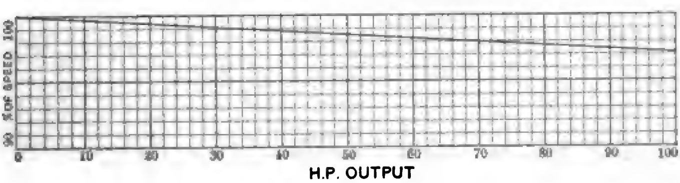


FIG. 118.

That current is delivered to the armature by induction is a striking feature, but not one that implies any radical difference in function.

It is not even necessary to use a polyphase circuit for working induction motors, for, under certain conditions, the same set of poles can perform the double duty of delivering current and interacting with it to produce torque.

The principles of the induction motor, as here given, become part of the general theory of the electric motor which applies alike to machines for continuous and alternating current, quite independent of particular methods of construction or operation.

The great pioneers in induction motor work, Tesla, Ferraris, and others, preferred to view the matter from the special rather than the general standpoint, and hold to the theory of the rotary pole action of induction motors—very beautiful, mathematically, but unfortunately hiding the kinship of induction to other motors, and distracting attention from the transformer action, which is so prominent.

From this point of view the two pairs of poles in Fig. 117 co-act to produce an oblique resultant magnetization, which shifts around the field, producing a moving system of poles, following the sequence of the current phases, and dragging around the armature after them, by virtue of the currents induced in it. Figs. 119, 120, 121 show the rudimentary principles of the rotary pole. In Fig. 119 an annular field magnet

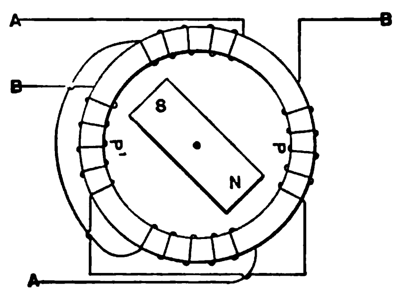


FIG. 119

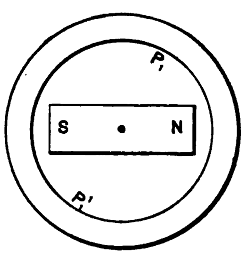


FIG. 120.

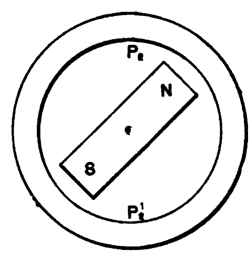


FIG. 121.

is wound with two circuits *A A* and *B B*, supplied with alternating currents 90° apart in phase. The polarity of the armature is represented diagramatically by the rotating magnet *N S*.

Now, when the current in *A A* is maximum (and that in *B B* is consequently zero), the field has poles at *P* and *P*,' which exert a torque on the armature poles. As the current falls in *A A* and rises in *B B*, the resultant poles move forward to P_1 and P_1' (Fig. 120), followed by the armature. When the current *B B* is a maximum, and *A A* has become zero, the poles are

at P_2 and P_2' and so on. In order that the revolving poles may induce current in the armature, the latter must slip behind so as to produce relative motion and change in electromagnetic stress.

This point of view is very interesting and instructive. It deals, however, not directly with the two field magnetizations,—the functions of which have just been discussed,—but with a resultant rotary magnetic field, which may or may not have a concrete existence, according to circumstances. It by no means follows that because two equal energizing currents are 90° apart in phase, they must or do form a resultant rotary magnetic field, or that, if they are so organized as to give a physical resultant, their individual functions are superseded and must be neglected.

As a matter of fact, the several currents in a polyphase induction motor may be so distributed that they cannot produce a resultant rotary magnetization, and in certain heterophase and monophase motors the "rotary field," in so far as one is formed, may revolve in one direction while the armature starts and runs strongly in the other direction. Hence the view here taken of the induction motor has been generalized for the purpose of bringing out its relation to the general theory of motors, and to take account of induction motors in explaining which the rotary pole theory would have to be, as it were, dragged in by the ears.

Salient poles, like those of Fig. 117, are seldom used, and the induction motor, as generally constructed, consists of two short concentric cylinders of laminated iron, slotted on their opposed faces to receive the windings. Sometimes these slots are open, and again they are simply holes close to the surface of the iron.

The relation of the parts is well shown in Fig. 122, a 6 HP two-phase motor by C. E. L. Brown.

In this case the exterior ring is the primary, and the revolving ring the secondary, element of the motor. The primary winding is of coils of fine wire threaded through the core holes, while the secondary member is wound, if one may use the term, with solid copper rods united at the ends by a broad copper ring. The clearance between primary and secondary is very small in all induction motors, almost always

less than ⅛ inch, sometimes less than $\frac{1}{32}$ inch. The smaller the clearance the better the machine as a transformer.

The primary of an induction motor is wound much as the armature of a polyphase generator is wound, as described already. Fig. 123 shows in diagram a two-phase winding for a 24 slot primary, and Fig. 124 a three-phase winding for the

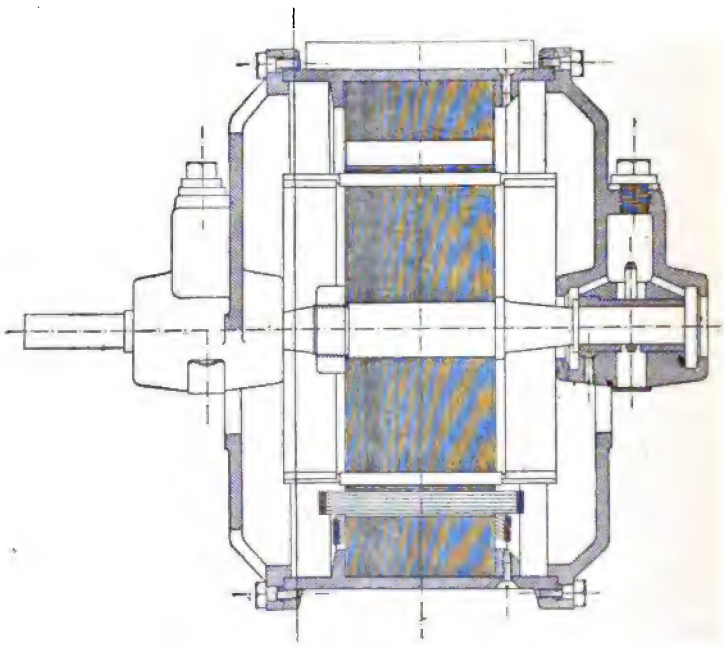


FIG. 122.

same primary. In the former there are two sets of coils *A* and *B*, each forming a separate phase winding; in the latter the three sets *A*, *B*, *C*, may be united to form either a "star" or "mesh" three-phase winding. In practice the primary winding is nearly always polyodontal, for the same general reasons that hold for generator armatures, but especially to keep down inductance. For the same reason the secondary winding is polyodontal. As an example of the best usage in this respect, Fig. 125 shows the number and relation of primary and secondary slots in the motor shown in Fig. 122. There are no

less than 40 primary slots for a four-pole winding, *i. e.*, 5 slots per phase per pole, while the secondary has 37 slots, this odd number being chosen to reduce the variation in the magnetic relations of primary and secondary due to different positions of the armature.

Induction motors with fixed primary have the great advantage of having no moving contacts, and no high voltage windings exposed to the strains due to revolution. On the other

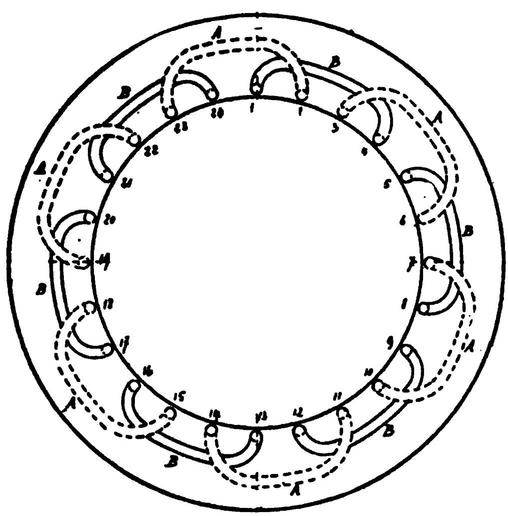


FIG. 123.

hand a revolving primary makes it very easy to vary the resistance in the secondary circuit, which is often desirable. Both forms are used in about equal degree. Inasmuch as a large proportion of the hysteretic loss occurs in the primary, since in the secondary the variation of the magnetization is small, a revolving primary, being of less dimensions than its secondary, gives a slight advantage in efficiency. There is, however, small reason to suppose that on the whole it is easier to build one form than the other for a given efficiency with the same care in designing.

Plate II shows a pair of induction motors of the American types. Fig. 1 is a 15 HP two-phase Tesla motor, manufactured by the Westinghouse Company. The primary is the revolving member, and receives current *via* the slip rings just outside the bearing. If resistance is to be inserted in the secondary, it can be done with a stationary rheostat.

Fig. 2 is a 125 HP three-phase motor, made by the General Electric Company. In this machine the secondary rotates.

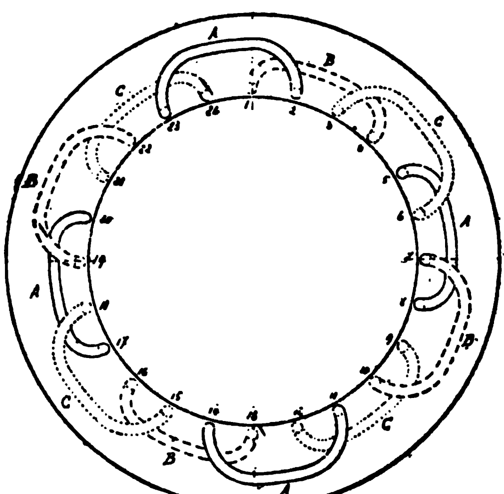


FIG. 124.

The short lever alongside the bearing moves a loose ring along the shaft, and thus serves to cut in or out a resistance in the secondary, which resistance is carried on the armature spider, and is generally in two or three sections, thrown in or out consecutively. With the lever placed as shown, all the secondary resistance is in circuit.

A glance at the plate shows that the secondary windings are by no means as simple as that of Fig. 116. They are true bar windings, not merely bars with a common connection.

It is evident that the currents generated in the secondary

are most useful when they flow so as to react most strongly with the motor field. So long as the winding of Fig. 116 (generally called "squirrel-cage") is employed, the armature currents are not organized accurately, but flow rather promiscuously. Such an armature does not give by any means the best results attainable, and, save in very small motors and for special purposes, it has been abandoned in this country in

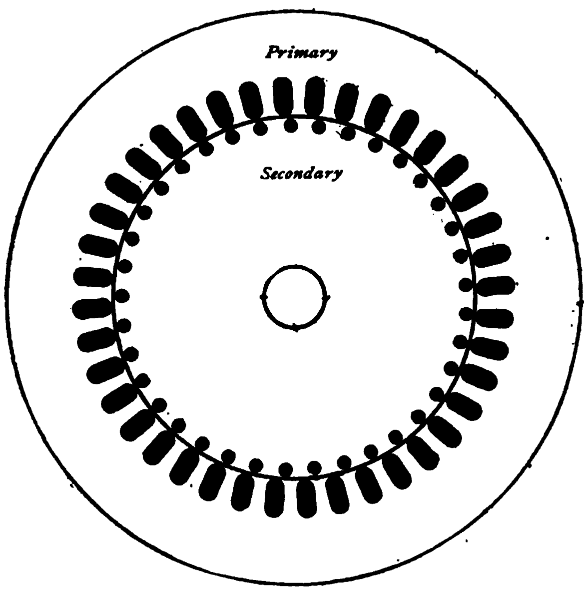


FIG. 125.

favor of a secondary winding very similar in character to the primary windings, but composed of massive bars joined by heavy copper end connectors. A four-pole, three-phase secondary winding of this character is shown in Fig. 126. It is obviously more troublesome to construct than a "squirrel-cage," but gives far better results.

In motors such as those just described, with distributed windings and no definite polar areas, the consecutive exchange of motor and transformer functions among the windings is almost lost sight of in the presence of the very apparent phenomenon of resultant revolving poles, but the appearance

of the latter is a necessary result of the persistence of the former. These induction motors are generally operated from the secondary circuits of transformers, although the large sizes (50 HP and upward) are sometimes wound for use of the primary voltage direct up to 2,000 volts or more.

Another form of induction motor which possesses some

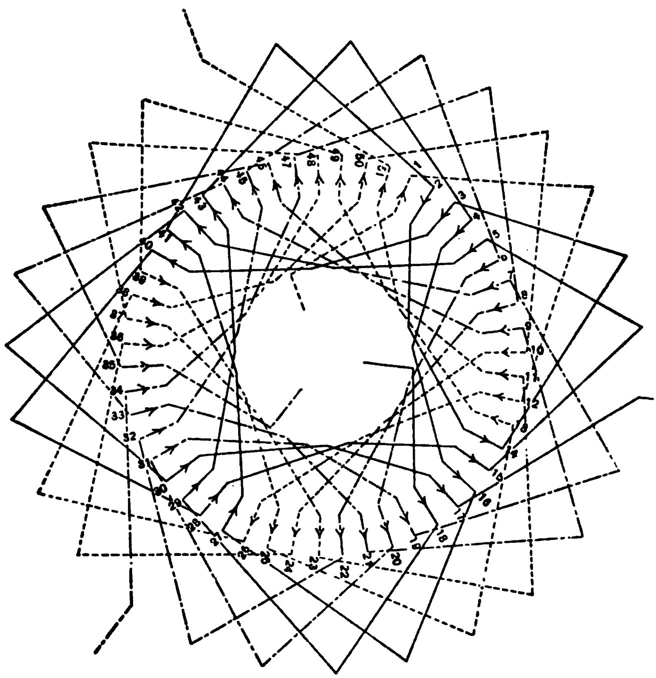


FIG. 126.

interesting features is the Stanley machine, shown in Figs. 127, 128. The field shown in Fig. 127 is composed of two separate rings of laminated iron, each having eight polar projections. These field rings are assembled side by side with the poles "staggered," as shown in the cut. Each field is energized separately, one from each branch of a two-phase circuit. The armature, Fig. 128, is composed of two separate cores assembled side by side. The secondary winding, polyodontal as usual, is common to the two cores. The transformer and motor functions are here entirely distinct, for each half of the

machine acts alternately as transformer and motor, one set of fields inducing current, which serves for motor purposes in the other half of the machine. There is no rotary field, no resultant of the two field magnetizations, nothing but the alternation of transformer and motor functions that is a characteristic of all polyphase induction motors.

These motors are generally used in connection with condensers to improve the power factor, and to facilitate this practice are usually wound for 500 volts.

The "monocyclic" induction motor is in structure similar to ordinary polyphase induction motors, but differs from them in

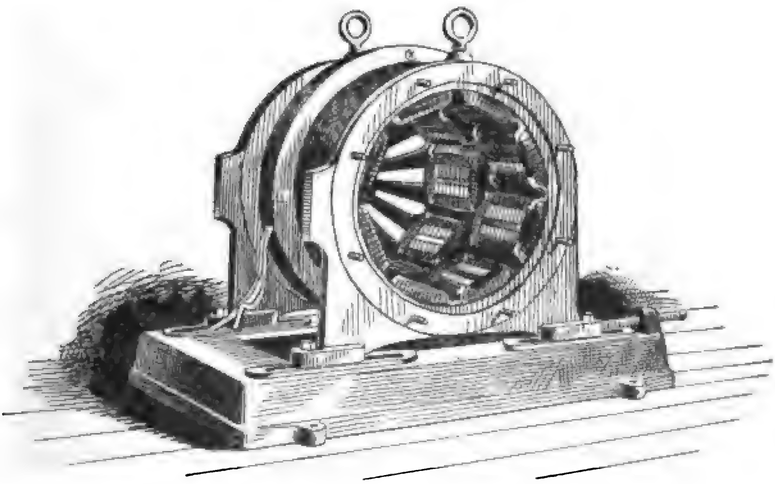


FIG. 127.

function, in that under normal running conditions the energy received by it is essentially monophase. Its principle can be best seen by referring to Fig. 117. Suppose that instead of winding the *A* and *B* poles alike, the *A* poles are proportioned so as to supply all the energy required by the motor, while the voltage supplied to the *B* poles is sufficient merely for magnetizing purposes—*i. e.*, it is so near to the counter E. M. F. of the revolving armature at normal speed that there can be no material transfer of energy. The *B* poles are then specialized as field poles, while the *A* poles serve in lieu of brushes to supply the energy. The magnetizing current for the *B* poles

is furnished by a separate circuit in order that the magnetization may be in phase with the armature current. The E. M. F. of this circuit is thus about 90° ahead of that of the power circuit, while the currents in the *A* and *B* circuits are nearly in phase. Only at heavy loads is there any material transfer of energy from *B* to the armature. The object of this rather singular construction is to confine the main distribution of

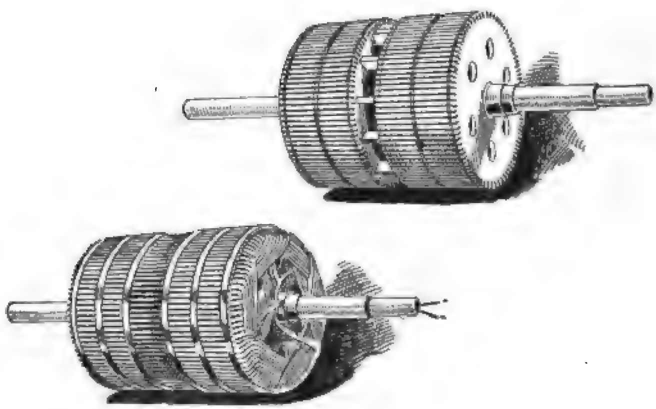


FIG. 128.

energy to a single circuit, the small magnetizing current being sent over a subsidiary wire of small cross-section, as already described.

A step further in the same direction of simplicity, but inferior to both polyphase and heterophase forms, are the true monophase induction motors. The principle of these motors is shown in Fig. 129. Here there is but one set of poles energized by the circuit *A*, while *b*, *c*, *d*, are portions of the armature winding, which may be a simple squirrel cage, or a complex bar winding similar to those used in polyphase motors.

If *A* be supplied with an alternating current, induced currents will be produced in the armature, out of phase with the field magnetization and symmetrical with respect to it, so that no torque is produced.

If, however, we spin the armature up to nearly synchronous speed, the armature currents will lag, from self-induction, behind the E. M. F. set up by the field, so that they have an

angular displacement with respect to the field at a time when the latter is still active. There is therefore torque between these two elements—*in the direction of the initial rotation.* The motor will thus run, when once started, equally well in either direction.

In every motor there must be not only a field magnetization and current in a movable conductor substantially in phase with each other, but there must be a stable angular displacement between the two in order to ensure continuous torque. In continuous current motors this displacement is secured by the position of the brushes. In polyphase induction motors it is obtained by the space relation of the sets of poles combined

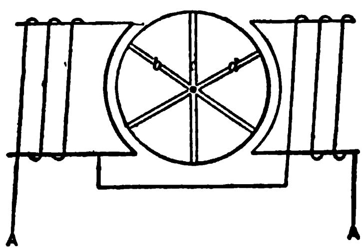


FIG. 129.

with the time relation of the two or more currents. In the monocyclic motor the currents are in phase, and the condition is like that in a continuous current motor with the substitution of inductor poles for brushes.

In the monophase motor this angular displacement is due to the displacement of the armature currents by inductance. Hence there is a particular value of the inductance corresponding to the best condition of torque, more or less than this being injurious.

In practice monophase induction motors are built in very much the same form as polyphase motors, and for the same reason, *i. e.*, to make the structure good as a transformer. In fact, the same motor structures are often used for both types. Fig. 130 shows the manner of winding a six-pole monophase primary, homologous with Figs. 118, 120. A monophase induction motor of 120 HP by Brown, Boveri & Co., is shown in Fig. 131. Monophase motors are not used to any extent in

this country, and abroad their use is generally confined to motors much smaller than the example shown.

A moment's reflection will show that while the supply of energy to a polyphase motor is substantially continuous, in some heterophase, and all monophase, motors it is essentially intermittent, so that these latter give less output for the same structure. The dependence of the torque on the existence and

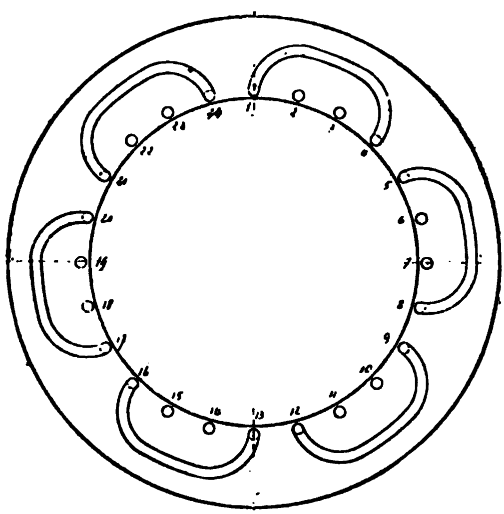


FIG. 130.

magnitude of the armature inductance, too, leads to low power factors and great difficulties in speed regulation—never too easy in induction motors.

As we have already seen, polyphase induction motors are self-starting. To give a monophase motor a definite starting torque is not a difficult matter. In normal monophase working there is no initial torque, and to obtain it some form of heterophase connection is generally used. The commonest method is to employ a set of subsidiary windings to produce temporary motor poles, with which the current produced by the main or inductor poles can react as in the polyphase systems.

When the motor reaches speed this subsidiary winding is cut out or thrown in series with the main winding, and the motor thereafter runs as already described. The starting windings are usually energized by a current out of phase with the main current, but derived from it, with a phase difference produced by a difference of inductance.

The practical properties of good modern induction motors

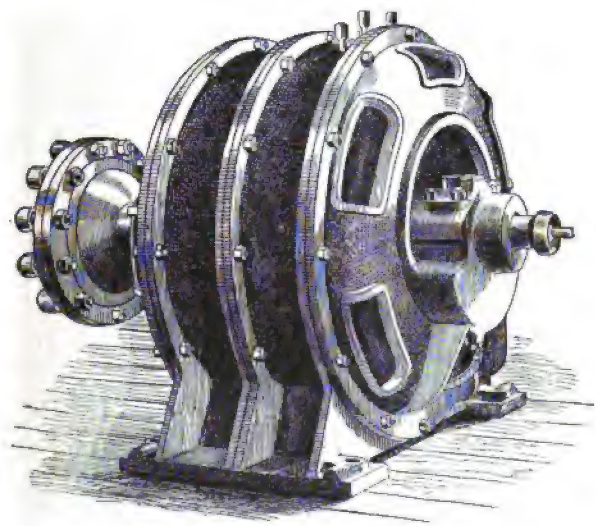


FIG. 131.

are strikingly similar to those of shunt-wound or separately excited continuous current motors.

For the same output, the induction motor generally has the advantage in weight, owing to the fine quality of iron which has to be employed, but its laminated structure and rather complicated primary winding make it fully as expensive to build, in spite of the absence of a commutator.

In point of commercial efficiency there is but little difference. It is not difficult to build an induction motor which is fully up to the average efficiency of other motors of similar output and speed. And what is of greater importance, the question of sparking being eliminated, the point of maximum

efficiency can quite easily be brought somewhere near the average load. It must be remembered that here, as elsewhere, the last few per cent. of efficiency are somewhat costly, and not always found in the rank and file of commercial machines.

The weak point of commercial induction motors is apt to be the power factor. Of course low power factor means demand for current quite out of proportion to the output, and hence greater loss in the lines and greater station capacity. In

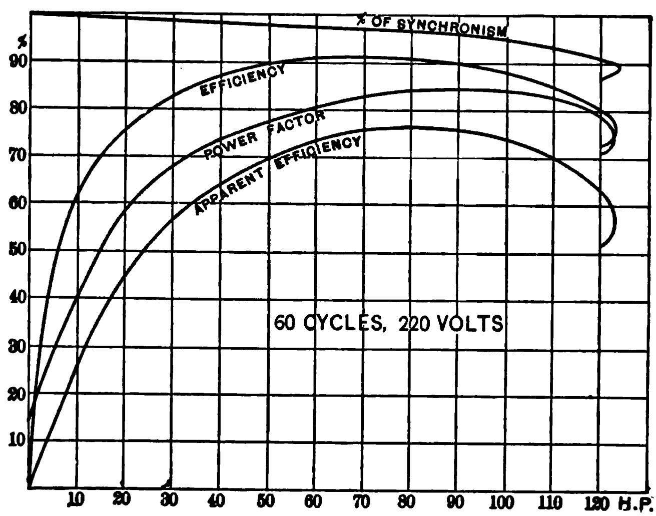


FIG. 132.

addition, a heavy lagging current makes regulation of voltage on the system anything but easy.

Now, it is perfectly feasible to build induction motors with power factors so high as to avoid these practical difficulties almost entirely. But this result is somewhat expensive, whether reached by *finesse* in design, or by the addition of condensers, and it is therefore not always attained.

Slow speed induction motors, large and small, are subject to bad power factors, and so in fact are all induction motors having many poles. The best results, however, are very good indeed. A power factor of .9 or thereabouts at normal load is quite unobjectionable in practice, and this figure can be reached or closely approximated by careful design.

In point of efficiency there is little difficulty in reaching satisfactory figures. The actual properties of polyphase induction motors can be best appreciated by the examination of their characteristic curves, showing the variations of efficiency, power factor, and speed under varying loads. Fig. 132 shows these curves for a 75 HP three-phase motor built by the General Electric Company. It is a 60~ motor, intended for severe service, and hence is arranged to carry considerable overload at a good efficiency. The fall in speed from no load to full load is

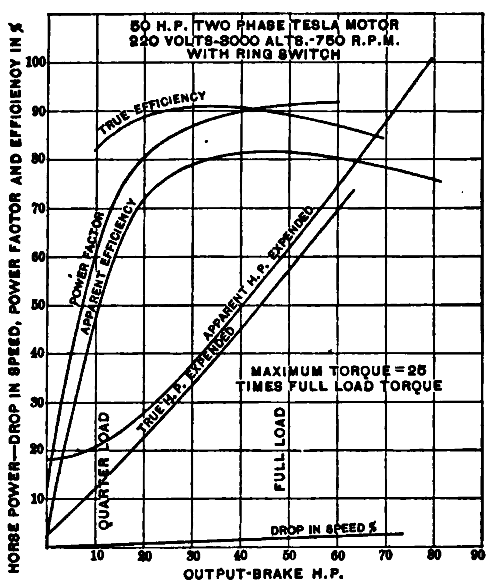


FIG. 133.

but 3 per cent., and the starting torque is 80 per cent. greater than full running torque, with an expenditure of current closely proportional to the torque. The commercial efficiency reaches 91.1 per cent., and the power factor 84.3 per cent., which is not bad for so large a motor intended for considerable overloads.

Fig. 133 shows the characteristics of a Westinghouse two-phase induction motor of 50 HP for 25~. Its properties, as might be expected of a well-designed motor for so low a frequency, are admirable, particularly the great efficiency at small loads.

Fig. 134 shows the properties of a polyphase motor of 201 HP at 130~, used with Stanley condensers to keep down the results of the inductance encountered at so high a frequency. The effect of this device, particularly at moderate loads, is very striking indeed. Without condensers one could not obtain such a power factor even at full load. While the condenser does not perfectly compensate for inductance, it does

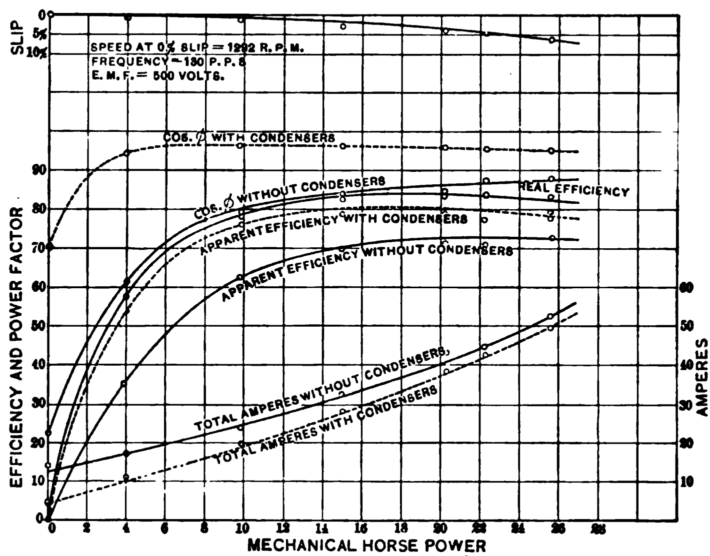


FIG. 134.

so sufficiently well for all practical purposes. In other properties the motor is not so especially remarkable.

These curves are from the manufacturers' tests, and the author believes them to be entirely trustworthy, although they probably represent good results. Better curves than these are occasionally obtained, generally for some individual reason. Now and then a "freak" motor is produced, with enormously high efficiency or power factor, like a certain 5 HP three-phase motor designed and tested by the author, which gave at full load a power factor of .94.

On the other hand, it is unfortunately true that many commercial induction motors are not as good in point of efficiency and power factor as they ought to be. A series of tests of

induction motors under the direction of Professor D. C. Jackson has recently been published, which gives data so instructive and impartial as to be well worth reproduction here. The motors tested were, except for a 10 HP Westinghouse two-phase, all of 5 HP nominal capacity, and by the following makers: Westinghouse, Fort Wayne Electric Corporation (synchronous self-starting monophase), Stanley, Allegemeine Electricitäts Gesellschaft, General Electric Company. In addition, results of tests on Oerlikon and Brown motors are included in the results. Fig. 135 shows the efficiency curves and regulation of

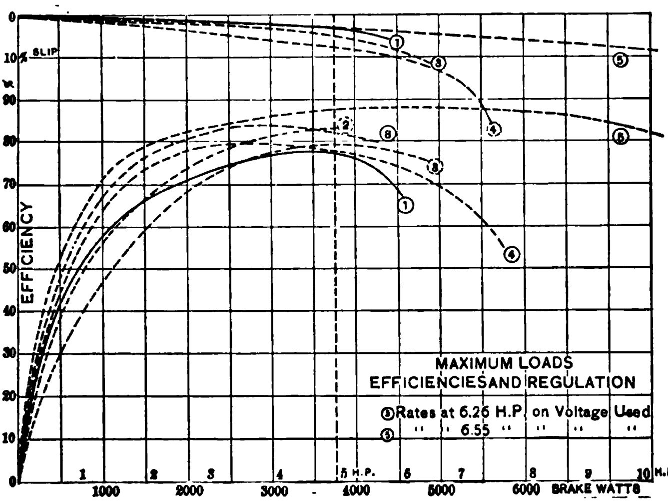


FIG. 135.

the several machines, and Table I on page 222 gives a general view of their respective properties.

Looking over these results, Nos. 3, 5, and 8 are decidedly the best of the lot. Of these No. 3 is possessed of a fairly high and very uniform power factor, but rather moderate efficiency. It starts well, and with a moderate current has sufficient margin of capacity for all ordinary work, but its speed falls considerably under load. No. 5 has extraordinary efficiency at all loads, starts admirably, and can carry a tremendous overload—more than double its rated capacity. Moreover, it regulates very closely. The power factor, however, is so bad as to be a curiosity, having apparently been sacrificed to

obtain great maximum output, which is for many purposes useless. No. 8 is a better all-around machine than either of the others, has a good maximum efficiency at a little below full load, and an excellent power factor. Professor Jackson notes that since, at an output of 3½ HP, No. 3 has an efficiency of 75.5, and a power factor of 83½, while No. 5 shows respectively 85 and 59, the station capacity for the latter must be considerably greater than for the former. That is, the apparent efficiency of No. 3, which determines the necessary station capacity, is 64 per cent., while that of No. 5 is 50 per cent.,

TABLE I.

COMPARATIVE QUALITIES.

Number.	Rated Capacity, H.P.	Rating at Voltage Used, H.P.	Torque, in % of Full Load. Max. Running.	Static.	Starting.	Starting Current, in % of Full Load.	Drop in Speed at Full Load, %.	Efficiencies—%. Max. Eff.	¼ Load.	½ Load.	¾ Load.	Full Load.	Power Factors—%. Max. P. F.	0 Load.	¼ Load.	½ Load.	¾ Load.	Full Load.
1	5	5	140	131	77	157	3	77.8	55.2	70.6	77	76.6	76.4	13	37.5	50	62.3	71.5
2	5	5	100	45	44	153		83.6	54.5	72.5	80.5	81.8	67.5	10.5	25.5	58	67.3	64
3	5	6.26	104	90	83	114	9.7	79	52	71.9	78.9	77	84	74	81.6	83.3	83.7	84
4	5	5	186.5	136	30.4	262	7	79.5	62.2	77.2	79.5	77.8	82.6	15.5	44.7	62.5	73.7	80.3
5	5	6.55	171	138.5	86.6	156	3.7	88	75.2	85	87.7	88	78.5	6.8	27.5	45.5	59.8	70.3
6	10	10	<147	142	137	104	4.5	82	67	78.4	81.9	81.1	70	15	40.4	59.1	69.	73.4
7	4.5	4.5	<163	232		357	3.7	79.1	61	73.8	78.4	79.1	88.4	22.2	51.3	60.4	80.3	85.2
8	5	5					4.6	83.8	65.5	80.2	83.8	82	89		52	71.5	81.7	87.2

NOTE.—6, 7 and 8 were not run up to maximum load, on test.

Hence to supply one brake HP with No. 5 motors, there must be a station capacity of 2 HP, while with No. 3 motors 1.56 HP is sufficient. But with No. 8 the efficiency is about .83, and the power factor about .80, giving an apparent efficiency of .66, which is better than either No. 3 or No. 5. Motors like No. 3 are excellent for the power station, but hard on the customer, while No. 5 is admirable for the customer, but bad for the station. No. 8 is fair to both parties.

Most of the motors shown start quite well enough for ordinary purposes. Neither heavy starting torque nor ability to carry large overloads are needed in ordinary motor work. Large torque per ampere is, however, desirable. It is best

secured by using at starting a non-inductive resistance in the secondary circuit. The effect of this is twofold: it limits the armature current to an amount which will not have a strong demagnetizing effect on the fields, and it advances the phase of this current so as to keep it in better position with respect to the motor poles. Only by the use of such a resistance is it possible to avoid very large currents at starting. With it it is quite possible to secure at starting the full load running torque of the motor without exceeding the full load current. This static torque will nearly always be more than enough to bring the initial load up to speed. An adjustable secondary resistance makes it easy to bring to speed any load that the motor will carry continuously, without demanding excessive current.

As to overload, an ability to carry 25 per cent. more than the rated capacity is ample, save in rare cases, and greater margin than this usually means some sacrifice in efficiency or power factor at normal loads. For most work an efficiency curve like that of No. 8 is preferable to one like that of No. 5. When great margin of capacity is needed, it is best to use a motor deliberately adjusted to such use, and not to expect it of a motor properly designed for ordinary service.

The speed of induction motors is best regulated by inserting a non-inductive resistance in the secondary circuit. Under these circumstances the motor can be made to run at constant torque over a very wide range of speeds by varying the resistance, just as one would regulate a street-car motor. Such a rheostat is used in operating hoists and the like with induction motors. Regulation by varying the primary voltage is highly unsatisfactory, since the torque falls off nearly in proportion to the square of the voltage, so that at low speeds the output is enormously reduced. Regulation by any method involving resistance is of course inefficient, not more so, however, than in the case of continuous current motors.

The weak point of induction motor practice is in the heavy inductance likely to be encountered unless motors with first-class power factors are used. It is depressing to find the current capacity of your generator exhausted long before it has reached its rated output in kilowatts, and if the motor service is part of a general system, the effect of a bad power factor on regulation is disastrous.

With generators of moderate inductance and good motors, general distribution by polyphase currents gives admirable results. The station manager should see to it that his motors are not of excessive size for their work, and are good in the matter of power factor. A few motors for very variable loads can be handled readily enough, but no motor with a bad power factor should be tolerated simply because it is cheap. Power factors of at least .85 at full load, and .80 at two-thirds load, are quite obtainable except in case of some special motors, and should be insisted upon rigorously.

One polyphase station operating more than fifty induction motors showed, when tested by the author, about .65 as average power factor when carrying all the motors. Rigorous inspection of the motors installed would have raised this figure to .75, although the existing power factor actually gave no trouble whatsoever.

So much for polyphase induction motors. Heterophase and monophase induction motors generally fail to give so uniformly good results. Occasional extraordinary results have been reported from the latter class, but in the author's opinion they concern motors which belong to the "freak" class alluded to, and cannot be expected in commercial practice. Monophase motors are usually weak in power factor, and start badly, most of those in use abroad being started without load. Even so, the starting current is large, as may be safely concluded from the discreet silence preserved on this topic in all descriptions of monophase motor installations. Such machines have not yet come into commercial use in this country. In general power transmission work the incandescent lamp and the induction motor are the chief factors. Synchronous motors are valuable in their proper place, and arc lighting and continuous current work are sometimes relatively important. The alternating current systems are now far enough developed to be entirely workable and trustworthy for incandescents and motors. The alternating arc lamp is, however, not yet in condition to replace the continuous current arcs generally used, and for work specially suited to continuous currents, reliance has at present to be placed in various current reorganizing devices, which are, so far, of rather indeterminate ultimate value. Whether they are to have a large permanent place in the art,

or whether their sphere will gradually be much contracted, is uncertain, although the author inclines to the latter opinion. At all events it is sufficiently clear that the main body of power transmission will have to depend on alternating currents.

Even if continuous current should be obtained somewhat directly from coal in the near or far future, the result would be not to increase power transmission by continuous currents, but to render the transportation of coal by far the cheapest method of transmitting energy.

The relative importance of polyphase, heterophase and monophase systems is a question often raised. The present indications are that the polyphase systems, in virtue of increased output of generators, possible economy in copper and general convenience, have come to stay. The monophase motor problem has not yet been satisfactorily solved in any general way, and until it has been solved, the monophase system must remain subordinate, like the heterophase systems, which are special rather than general in their applicability. The much mooted question of frequency will be referred to in its different bearings in connection with other topics. The frequencies once common, 120~ to 135~, are rapidly passing out of use for all important work. They are inconveniently high for long lines, by reason of inductance, are troublesome for large units, lead to high inductance in the system, and have for their only compensating advantage, lessened cost of transformers. Both here and abroad lower frequencies have come into use. In this country 60~ to 65~ seems to be the favorite range, except for work with rotary converters, when 25~ to 35~ are usual. Both these last are too low for general practice, since the cost of transformers is greatly increased; the former is unsuitable for incandescent service, unless with extremely low voltage lamps, and both are unsuitable for alternating arcs.

On the other hand, abroad a compromise frequency of 40~ to 50~ is in general use. In the author's opinion there are very few cases in which lower frequencies than these are desirable, and none in which less than 30~ should be tolerated; 50~ to 60~ meets general requirements admirably, and only in rare cases is the use of rotary converters of sufficient importance to call for a lower frequency.

In connection with this topic we may consider a verbose controversy which has raged of late, respecting the advantages of certain irregular forms of alternating current waves *vs.* a true sine wave. The facts in a nutshell are as follows: Certain complex current waves, whose irregularity is due to the presence of harmonics of higher frequency, have been found to give slightly better efficiency in transformers than sine waves of the same nominal frequency. Such waves, however, do not hold their form under varying conditions of load, and by reason of their harmonics of higher frequency raise the inductance of the line and apparatus, increase the probability of resonance on the line, disorganize all attempts to balance the inductance of the system by condensers or synchronous motors, and finally interfere with the proper performance of induction motors. The use of such wave forms, then, is likely to lead to very embarrassing complications in a power transmission system, and their sole advantage is far better secured by using a sine wave of slightly increased frequency, than by interpolating a set of worse than useless harmonics.

It is needless to say that all cases of power transmission cannot be treated alike—there is no system that will meet all conditions in the best possible manner. The best results will be obtained by treating, in the preliminary investigation, each problem as an unique and independent case of power transmission, and afterward boiling down the conclusions to meet practical conditions. Avoid, when you can, apparatus of peculiar sizes and speeds—remember that you are after results, not electrical curios. See to it that what is done is done thoroughly, and for general guiding principles keep your voltage up and your inductance down, and watch the line.

CHAPTER VI.

CURRENT REORGANIZERS.

WHATEVER method may be employed for the transmission of power in any given case, it will often be found that the current delivered at the receiving station is not of the character needed. Sometimes in transmissions for special purposes no difficulty will be met, but frequently, especially in the transmission of power for general distribution, both continuous and alternating currents are needed, whereas only one is at hand. For all electrolytic operations, for railway work at present, for telegraphy, and generally for arc lighting, continuous current is necessary, while alternating current is necessary for convenient application to electric furnaces, electric welding, electro-cautery and other minor purposes. So whichever kind of current is transmitted the other must be derived from it for certain uses.

All devices for thus changing alternating to direct currents, or *vice versa*, with or without accompanying change of voltage, may properly be called *current reorganizers*.

Three classes of such apparatus have come into more or less use: 1. Commutators; 2. Motor dynamos; 3. Rotary converters or transformers. These classes are quite distinct from each other; each has advantages and faults peculiar to itself, and all three are in every-day practical use to a greater extent than would seem probable at first thought.

We have already looked into the matter of commutation in Chapter I., and have seen how the naturally alternating currents in a continuous current dynamo are rectified and smoothed. Given, then, an alternating current received from a distant generator, and it would seem an easy matter to receive this current upon a commutator and deliver it as continuous current. In point of fact there are very serious difficulties in this apparently simple process.

The current received is a set of simple alternations shown

diagrammatically in Fig. 136. The figure shows three complete periods. Now if such a current be sent into a simple two-part commutator, such as is shown in Fig. 10. Chapter I., revolving

FIG. 136.

at such a speed that the brushes will be just passing from one segment to the other every time the current received changes direction, the result will be a rectified current, shown in Fig. 137, unidirectional, it is true, but far from continuous. Vari-

FIG. 137.

ous modifications of this simple rectifying apparatus have been and are in extensive use for supplying current to the field magnets of alternating generators. As these machines are generally multipolar, the two-part commutator has been modified so as to reverse the current at each alternation. Fig. 138 shows one of the simple forms of commutator arranged

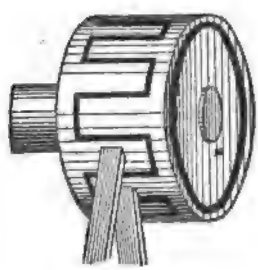


FIG. 138.

for self-exciting alternators. It consists of a pair of metal cylinders mounted on and insulated from the dynamo shaft. Each cylinder is cut away into teeth, and the two are mounted so that the teeth interlock with insulation between them. Each pair of consecutive teeth acts like the ordinary two-part commutator, and there are of course a pair of teeth for every pair of poles, so that the commutator acts at each alternation.

The resulting rectified current is then led around the field magnets of the generator, furnishing the whole excitation, or enough to compound the machine. Such a current, however, is so fluctuating that it is by no means the equivalent of an ordinary continuous current for magnetizing purposes, hence in most modern machines the main exciting current is furnished by a small exciting dynamo, driven from the alternator shaft or by separate means, while the rectified current is used only for compounding.

This simple current reorganizer is very successful for the purpose described. But it must be remembered that the amount of energy concerned is trifling, only a very few kilowatts being required to compound even the largest alternators. And despite this, there is often trouble from sparking, such commutators being notoriously hard to keep in good order.

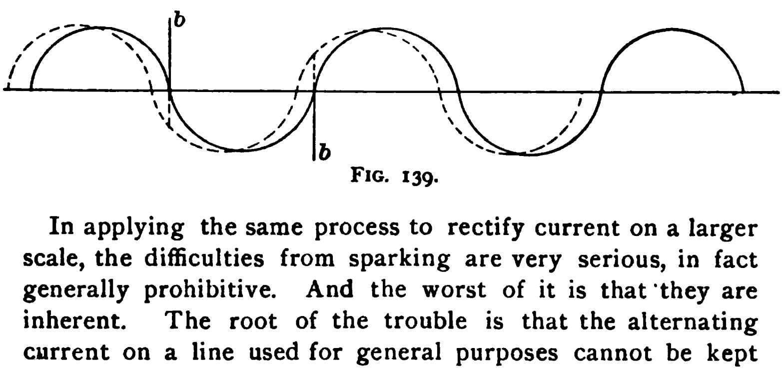


FIG. 139.

In applying the same process to rectify current on a larger scale, the difficulties from sparking are very serious, in fact generally prohibitive. And the worst of it is that they are inherent. The root of the trouble is that the alternating current on a line used for general purposes cannot be kept accurately in step with the motion of the commutator. To ensure sparkless commutation the conditions must be as shown in Fig. 139.

The alternations of the current and E. M. F. are shown by the solid line, while the brushes at the moment of passing from one commutator segment to the next must take the position *b b*, with respect to the current. That is, they must pass from one segment to the next at the moment when the current, just reversing, is practically zero. So long as the electromotive force and the current are in phase with each other, as shown in the solid line, the current will be rectified without noticeable sparking. But when the current lags behind the E. M. F., as shown by the dotted line of Fig. 139, there is trouble

at once. The brushes, as can be seen from the dotted prolongations of *b b*, must break a considerable current, and there is certain to be sparking. Nor can any point be found for the brushes at which they will not have either to break this current or to pass from one segment to the next while there is considerable E. M. F. between segments. The case is bad enough in a compounding commutator having a position fixed with reference to the E. M. F. of the machine and dealing with low voltage and moderate current. The inevitable result is sparking that can be only mitigated by shifting the brushes, and more or less demoralization of the compounding. If the current be received from a distant generator on a commutator driven by a synchronous motor, the condition of things is much worse. When the current lags (or leads), not only are the brushes generally thrown out of step with it, but if there is a sudden change of phase the inertia of the commutating apparatus will put it at serious variance for the time with both current and E. M. F. Add to this the disturbances of phase produced by armature reaction in both generator and motor, and one has a set of conditions that renders sparking absolutely certain. The most that can be done to help matters is to employ palliative measures to delay the destruction of the commutator. Aside from this sparking, it is nearly out of the question to hold the voltage of the rectified current steady if the phase is shifting (as it often is likely to be).

Incidentally may be mentioned the fact that in working such a commutating apparatus, the direction of the rectified current will be uncertain; the brush which happens to be on a positive segment when the brush circuit is closed, will stay positive, as can readily be seen by tracing out the rectifying process in Fig. 138. In ordinary compounding commutators this uncertainty is absent, for with the brushes in a fixed position the positive segments will always be under the same brush, since the segments are fixed with reference to the armature coils.

No small amount of time and money has been spent in trying to work out a successful synchronizing commutator. The main trouble is, of course, sparking, and the exasperating part of the problem is that while on a small scale, as in compounding alternators, fair results can be obtained, the difficulties increase enormously with the output, so that every attempt on

a scale really worthy of serious consideration has ended in discouragement and the scrap heap.

The great usefulness of such apparatus if of reasonably good qualities has made this field of experimentation very interesting, and a vast amount of ingenuity has been expended in elaborately devised plans for reducing sparking and minimizing the evil results of shifting phase. An example of such work, of more than usual merit, was shown at the International Congress of 1893 at Chicago. This was the current reorganizer devised by C. Pollak, for use in connection with accumulator installations. It was intended specifically for charging accumulators, and is very ingeniously adapted to that use. Its general appearance is shown by Fig. 140. The apparatus consists of a

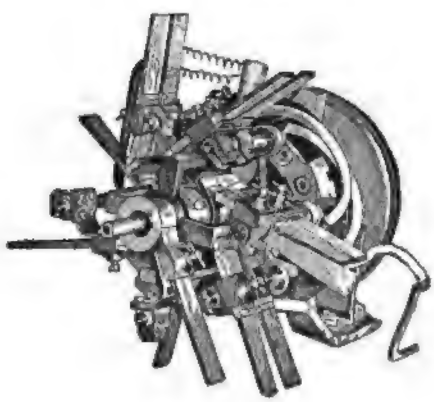


FIG. 140.

small synchronous motor driving a commutator, which has, in the example shown, eight segments coupled alternately in parallel so as to produce the effect of Fig. 138. The Pollak commutator is, however, peculiar in that the spaces between segments are of nearly the same width as the segments themselves, while the collecting brushes are set in pairs, so that by setting one of each pair ahead of, or behind the other, the ratio of segment width to space width can be changed. In charging accumulators the E. M. F. of the charging current must always, to prevent waste of energy, exceed the counter E. M. F. of the battery. Hence a current rectified as in Figs. 136 and 137, can-

not successfully be used. The arrangement of segments just described enables the brushes to be so set that contact with a segment is made at the moment when the rising E. M. F. of the alternating side is exactly equal to the counter E. M. F. of the battery, and broken when the falling E. M. F. reaches the same value. Only that part of the current wave of which the E. M. F. exceeds the counter E. M. F. of the battery is used, the charging circuit being open during the remainder of the period. When well adjusted and used on a circuit nearly non-inductive, the machine in question is almost sparkless and very well adapted for the particular purpose intended. It is also highly efficient, the only losses being those in the motor, *plus* brush friction. The total amount of these need be but trifling, probably less than 5 per cent. of the output.

But such apparatus cannot be considered as a general solution of the problem, for while quite successful for an output of 10 KW or so, it has not been tested in large sizes, nor under the conditions of inductance ordinarily to be expected on a power transmission circuit. For the reasons already adduced the chances for success are not good, particularly since all questions of sparking become very grave when large currents must be dealt with. This difficulty is well known in dynamo working. For instance, in an arc machine there may be frequent recurrence of the long, wicked-looking, blue sparks familiar to every dynamo tender, without noticeable damage to the commutator, while in a low voltage generator sparking of much less formidable appearance may put the machine *hors du combat* in a very short time.

Bearing all this in mind, it is but natural to expect that another particular solution of the reorganizing problem might be found for arc lighting. Here the irregularity of a "rectified" current is of small consequence, while the small amount of current cannot cause really destructive sparking if other conditions are fairly favorable. So it is that we find commutating apparatus in quite successful use for arc lighting in connection with alternating stations. The form of apparatus shown in Fig. 141, designed by Ferranti, has been introduced in several British stations with good results. The commutating mechanism is of course used in connection with a "constant current" transformer, arranged so as automatically to hold

the current closely uniform under all variations of load. Each commutating unit supplies two separate arc circuits of moderate capacity—twelve lights in each. How well the same device works at several times the E. M. F. necessary to supply so small a series, is now being demonstrated. The present tendency in central station practice is to employ very high voltages for arc lighting—50 to 100 or 125 lamps in series, thus greatly simplifying both the station equipment and the circuits. The rectifier should at least be able to replace the smaller generators now in use and such machines are now built for as many as sixty lights. This is probably practical—in

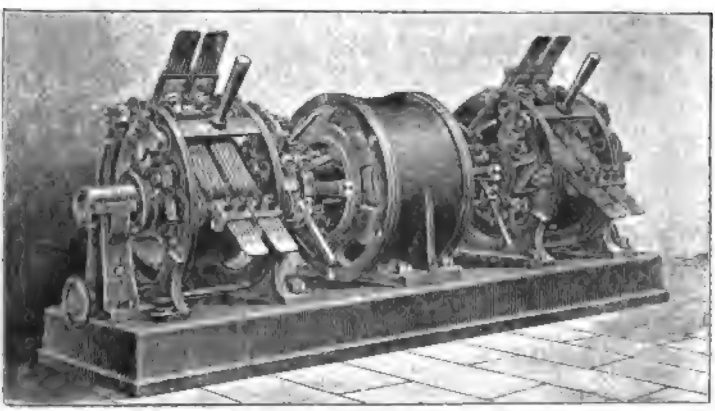


FIG. 141.

fact there seems to be no good reason why the rectifier should not be entirely available wherever it is desirable to work series arc circuits in connection with a transmission plant. Although the apparatus has not been in use for a sufficiently long time to enable one to pass a final judgment upon it, it is at least promising and worth careful investigation. It is possible that the alternating arc lamp will be developed far enough to render continuous current arcs unnecessary, but to put the matter mildly, this remains yet to be proved.

All rectifying commutators now in practical service are of very limited output—not much exceeding 10 to 15 KW, an amount merely trivial so far as large enterprises are concerned. For railway work or incandescent lighting, these very interest-

ing machines cannot be considered in the race at present. The general problem is as yet unsolved by such means, useful as they may be for special purposes.

The current delivered by rectifiers is in a measure discontinuous, and, hence, is not the full equivalent of an ordinary continuous current. The Pollak machine, however, which is intended to be used with a somewhat flat-topped alternating current wave, has been successfully employed for working motors as well as for charging accumulators. It is not impossible that such apparatus may yet be constructed of sufficient capacity to be of much practical service, although the difficulties, as has already been pointed out, are very considerable, and of a kind very hard to overcome. Of course, polyphase currents can be rectified by following the same process as with monophase current, and a successful apparatus would often find a place in transmission plants.

The advantages of the rectifying commutator are simplicity, efficiency, and cheapness, particularly the last. The working parts are a small synchronous motor, made self-exciting (and self-starting) by a commutator, and one or more rectifying commutators driven by this motor. To obtain 100 KW output, it is not necessary, as in other forms of current reorganizers, to have a machine at least as large and costly as a 100 KW dynamo. On the contrary, a two or three horse power motor would be amply powerful to drive the commutator, and the whole affair could hardly cost a quarter as much as a dynamo of the same capacity, besides being of greater efficiency. But a hundred kilowatts is far beyond the output of any rectifier that has yet been put to commercial service, and even a hundred kilowatts is but a fraction of the output that is often desirable in a single unit.

On the other hand a rectifier must require at least the same care as a dynamo, and must in every practical case be employed in connection with reducing transformers to bring the alternating current to the right voltage. The regulation too, is somewhat dubious, since compound winding is out of the question. And the current is at best disjointed, likely to produce needless hysteresis, and of a character rather hard to measure conveniently.

To sum up, the rectifying commutator, while quite good

enough for certain particular purposes, has so far given no definite promise of general usefulness. All of the serious attempts to develop it on a considerable scale have ended in failure. It is not effectively reversible, so that the task of converting continuous to alternating currents is quite beyond it. While the cheapness, lightness and efficiency of such apparatus puts it in these particulars far ahead of any other type of current reorganizer, the verdict of experience has so far been adverse in spite of these advantages, and engineers have been driven to other and more cumbersome devices.

The most obvious method of deriving continuous from alternating currents, is to employ an alternating current motor in driving a continuous current dynamo. The two machines may be connected in any convenient way, by belting, clutching the shafts together, or by putting them in even more intimate connection by placing two armatures on the same shaft or two windings on the same core.

The procedure first mentioned is not infrequent, particularly when a transmission of power plant is installed in connection with an existing lighting or power station. A synchronous motor is installed in place of the previously used engines, belted in any convenient way to the existing generators, and the operation of the station goes on as before. Good examples of this practice may be found at Walla Walla, Wash. (monophase), Springfield, Mass. (two-phase), Taftville, Conn., and Sacramento, Cal. (three-phase). Further description is unnecessary, as the apparatus is in no way out of the ordinary, and not at all specialized for the conversion of alternating to continuous currents.

A more interesting way of accomplishing the same result is by the use of a twin machine comprising motor and generator on the same bed plate, or even on the same shaft. In this way the reorganizing apparatus is formed into a compact unit, convenient to install and to operate, and possessing an efficiency higher than that of two belted machines, by the belt losses and more or less of the bearing friction. The total increase of efficiency is perhaps 5 per cent., when the comparison is between a pair of coupled machines and a pair directly belted, or more if the belting be indirect. Moreover the motor and dynamo parts of the machine can each be

designed so as to give the best efficiency and economy of construction possible at the given mutual speed. A typical unit of this class is shown in Fig. 142—a Siemens continuous alternating transformer. The motor part is wound for 2,000 volts, monophase, and the dynamo part, of the well-known Siemens internal pole type, with overhung armature and brushes directly on the windings, delivers continuous current at 150 volts. In this case the machine has three bearings, although in many cases it would be quite possible to get along with two. The main advantage of this duplex form of machine is

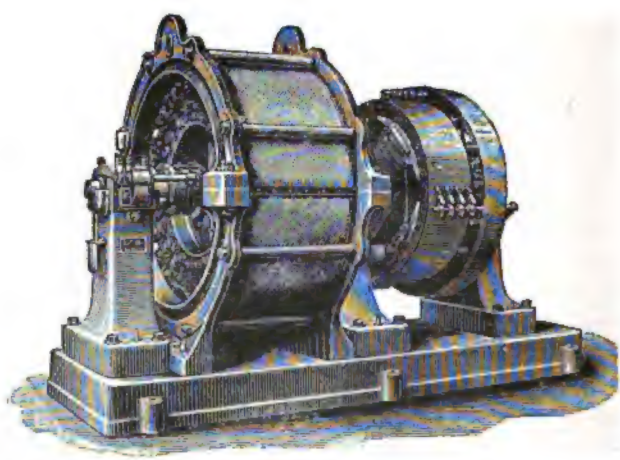


FIG. 142.

the complete independence of the two component parts in their electrical relations. The motor part can be designed for any desired voltage or number of alternations. It can often, except in very long transmissions, take the line voltage directly without need for reducing transformers, while the number of alternations can be chosen solely with reference to general conditions and without considering the direct current end of the machine at all. This, as will be seen when we have considered some other types of current reorganizers, is a very valuable property, since it gives the power of obtaining continuous current in a thoroughly practical way from alternating currents of any frequency. Other reorganizers can be worked

to advantage only within a somewhat limited range of frequency. Again, the motor-dynamo can be compounded on the continuous current side without in any way reacting upon the alternating circuit. and the two circuits can be regulated independently in any desired manner. All difficulties due to lagging current can be eliminated, and the continuous current side can be kept at constant pressure irrespective of loss in the main line or any variations of voltage or phase occurring in it.

Finally the apparatus can as readily give alternating current from continuous, as the reverse, and with the same independence in each case.

The compensating disadvantages are high first cost and rather large loss of energy in the double transformation. As to the former count, it may be said that the advantages gained in possible range of frequency and flexibility in the matter of voltage go far to offset the increase of cost. Often such a motor-dynamo is the only possible way of securing the necessary current. For example, if one wished continuous current for heavy motor service, such as hoists and the like, where the only current available was monophase alternating of the usual 125~, or even of 60~ for that matter, the motor-dynamo would be the only way of solving the problem.

As regards efficiency the motor-dynamo should be, and is, a little better than motor and dynamo separately, owing to lessened friction of the bearings. Its efficiency should be as great as 85 per cent. at full load, and might easily be 2 or 3 per cent. higher, in large machines. At half load it should be say 82 to 85 per cent. Practice too often shows results several per cent. below those mentioned, but this is because motor-dynamos have usually been of very small size and sometimes have been made up from any machines of the right speed that were at hand.

The usual synchronous motor may in small motor generators be replaced to advantage by an induction motor, which is simpler than the synchronous form and requires no brushes. Such a combination is shown in Fig. 143. This machine is intended for supplying the current for a large telegraph office. The motor is a three-phase induction machine of 2 HP output, operated from a 110-volt secondary at 50~. The speed

is a trifle less than 1,500 revolutions per minute. With this arrangement the attention required is very trifling, and a large number of troublesome batteries are displaced.

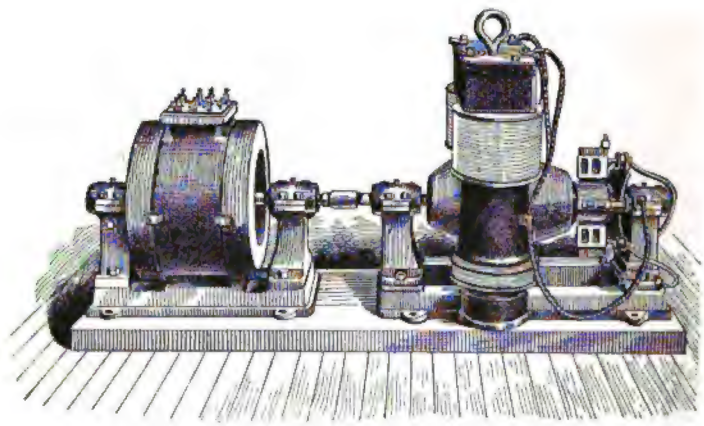


FIG. 143.

From the duplex machines just described it is but a short step to the composite dynamotor, so called, of which the armature is double wound. The primary or high voltage winding may of course be either alternating or continuous. The secondary winding is likewise for either current, and may well be fitted with both commutator and collecting rings. A favorite arrangement of the windings is to place the secondary coils in slots in the armature core, apply a sheathing of insulation, and then to wind the primary coils on the smooth surface thus formed. The commutators or rings are placed one at each end of the armature, as in the continuous current transformer shown in Chap. III., Fig. 35.

A typical dynamotor of this sort is shown in Fig. 144. This is specifically intended to derive a high voltage alternating current for testing purposes from a low voltage continuous current. The output is small, only a fraction of a kilowatt, and the armature is in the ordinary bipolar field used for small motors. The motor or primary winding is for 110 volts, continuous, and the secondary for 5,000 volts, alternating. Of

course these voltages might be anything desirable, since in so small a machine there are no difficulties in the way.

Another excellent specimen of the same type is Fig. 145, a Lahmeyer "*umformer*" of about 30 KW output. It is primarily a continuous current transformer, with 675 volts primary

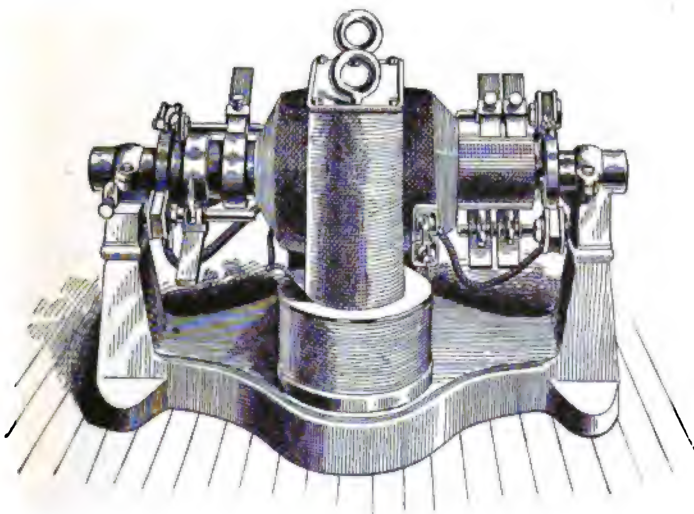


FIG. 144.

and 115 volts secondary. It is fitted, however, as shown in the cut, with collector rings outside one of the bearings, from which three-phase current at about 70 volts can be taken. There are four field poles, and as the normal speed is 850 revolutions per minute, the three-phase current is at a frequency of a little less than 30∼ per second.

This was one of the machines exhibited at the Frankfort Exposition of 1891, and fortunately an efficiency test of it is available, dealing, however, only with continuous currents. From the nature of the case the efficiency with a three-phase secondary would not differ substantially from that found, so that the curve, Fig. 146, gives a closely approximate idea of the general efficiency of such apparatus. At full load the commercial efficiency is very nearly 85 per cent., while at half load it has dwindled to 77 per cent. This is not bad for a small machine, and in a unit of 100 KW or more could undoubtedly

be raised several per cent. It should be at least as high as can be obtained from a duplex motor dynamo, in fact rather higher, since the bearing friction and core losses are diminished. The composite machine is also cheaper, since but one field is used, and it has a certain advantage in that the armature reactions due to the motor and dynamo windings tend to oppose each other, and hence to diminish possible sparking and disturbance of the field. It has the same independence of primary and secondary voltage as the duplex motor dynamo.

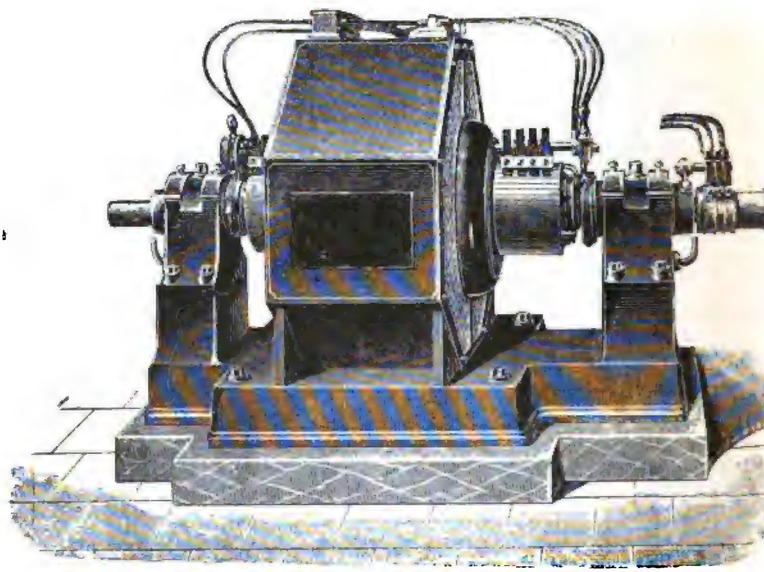


FIG. 145.

On the other hand, by reason of a common field, the periodicity of the currents in both windings must be the same. It must be remembered that a continuous current armature has a periodicity just as truly as an alternating armature. The current as generated in each is alternating, but in the former it is commuted before leaving the generator. Now the frequency of these alternations depends directly on the number of poles and the revolutions per minute, being in fact the numerical product of the two. So if one of these composite dynamotors be used with the continuous current winding as primary, the

frequency of the alternating secondary is fixed, since the speed of the machine cannot be changed without involving both primary and secondary voltages. If the alternating current side be used as the primary, the speed of the machine is fixed by the number of alternations, and whatever the voltage of the secondary, the frequency must be the same as that of the primary. Now it is a fact well known to dynamo designers, that continuous current dynamos generating a high frequency current prior to its commutation are troublesome and costly to build. Most continuous current dynamos have an intrinsic

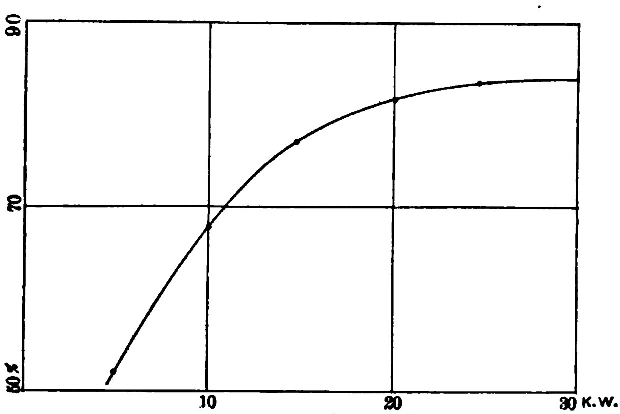


FIG. 146.

frequency of 15 to 25~ per second. To increase these figures to 40~ involves material difficulty, particularly in large machines, while 50 or 60~ are extremely hard to reach, unless in sizes of 50 KW and below.

Hence in spite of the good points of the composite dynamotor, it is of limited utility compared with the duplex machine previously described, particularly since there is a simpler way of doing the same work with a higher efficiency.

This is found in the so-called rotary transformer or converter (the names are in no wise descriptive).

This machine is nothing more than a continuous current dynamo fitted with collecting rings in addition to the commutator. These rings are connected to appropriate points of

the armature winding, and supplied with alternating currents of the same frequency which would be generated by the armature if the machine were used as a dynamo. The brushes being raised, the machine is nothing but a synchronous motor running without load at its normal speed. Now when the brushes are put down, the alternating current simply flows through the armature just as if it were generated therein, is commuted and passes out upon the line. This commutation takes place under just the same general conditions as if the machine were used as a generator. Meanwhile a portion of the current supplied is passing as before, not through the brushes but through the winding to the collecting rings, keeping up the action as a motor. Of the total current then, a small part forces its way against the E. M. F. set up in the windings by the field, and supplies the motor function; a far greater part, in amount determined by the resistance and inductance of the armature, flows as if urged by this E. M. F., to the brushes, and supplies the generator function of the machine. Thus a single armature winding serves to drive the armature and to furnish a large output of commutated current. And this current is not simply rectified, but is of exactly the same character as if generated in the armature.

The character of the winding in a rotary transformer is generally precisely the same as in a continuous current generator, the only addition being two or more leads from symmetrically placed points in the winding to the collecting rings. These leads can be so arranged as to form a monophase system for the alternating current or, if desired, a two- or three-phase system. The latter forms are generally preferred, since like the corresponding synchronous motors they are self starting, while the monophase machine has to be brought to speed by special means. Fig. 147 shows the character of the armature in a simple bipolar rotary transformer (monophase). Here the continuous current winding is a Gramme ring in 16 sections. From the brushes *B*, *B*, continuous current may be applied or withdrawn, while the brushes on the collecting rings *C*, *C*, perform the same office for the alternating current. Such a machine may serve a variety of purposes as follows: 1. Continuous current dynamo. 2. Alternating current dynamo. 3. Continuous current motor. 4. Synchronous alternating motor. 5. Con-

tinuous alternating transformer. 6. Alternating continuous transformer.

Diphase rotary transformers are usually supplied with four collecting rings connected to form two circuits, each one join-

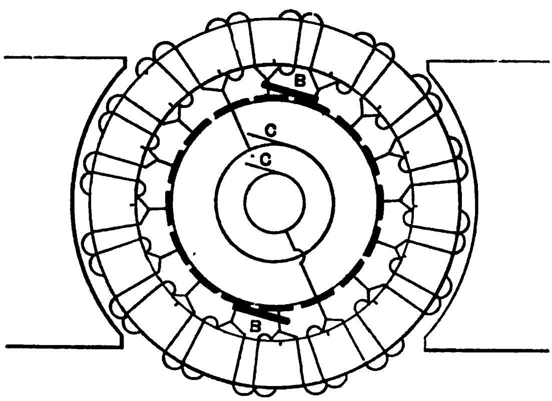


FIG. 147.

ing the windings in two opposite quadrants of the armature. Triphase transformers generally have three collecting rings, with their respective leads tapped into the windings 120° apart. The connections vary somewhat for different kinds of armature windings, but are the same in effect as those just indicated. One of the early practical machines of this sort exhibited at the Frankfort Exposition of 1891 is shown in Fig. 148. It is of the flat ring type usual to dynamos of Schuckert make, and is fitted with four collecting rings outside the bearing at the commutator end. The rings were arranged for either monophase or diphase connection. The rotary transformer thus organized attracted great attention, and was successfully operated in its manifold and diverse functions. It should be noted that if driven as a dynamo, such a machine can furnish continuous and alternating currents simultaneously, a property sometimes convenient though not often made use of.

These rotary transformers in the diphase and triphase forms are playing an important part in electric railway operations involving considerable distances, and a number of them are in highly successful use. A good idea of the modern type of rotary transformer is shown in Fig. 2, Plate III. This is one of

the 400 KW machines installed to operate the electric railways in the city of Portland, Ore. It is designed to deliver continuous current at nearly 600 volts, and receives its energy from Oregon City, about fourteen miles away, where is installed a triphase transmission plant. The motive power is derived from the great falls of the Willamette River. Current is generated at 6,000 volts, with a frequency of 33~ per second, and is given to the rotary transformers at about 400 volts, from the secondaries of the reducing transformers. Fig. 1,

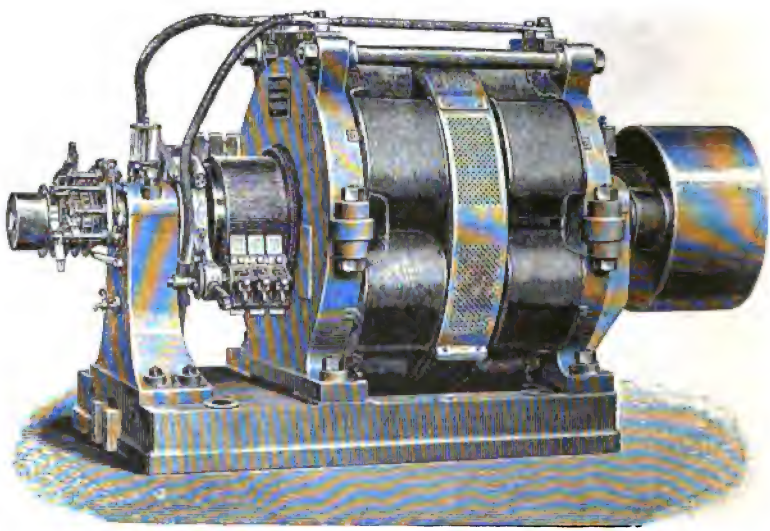
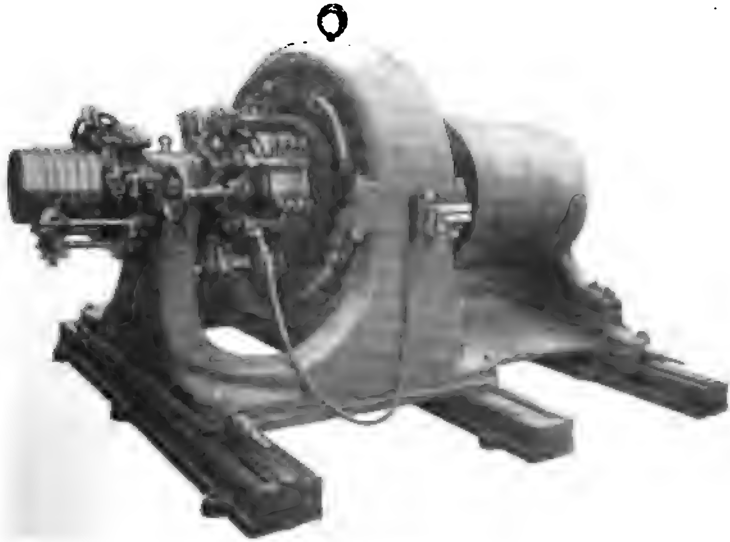
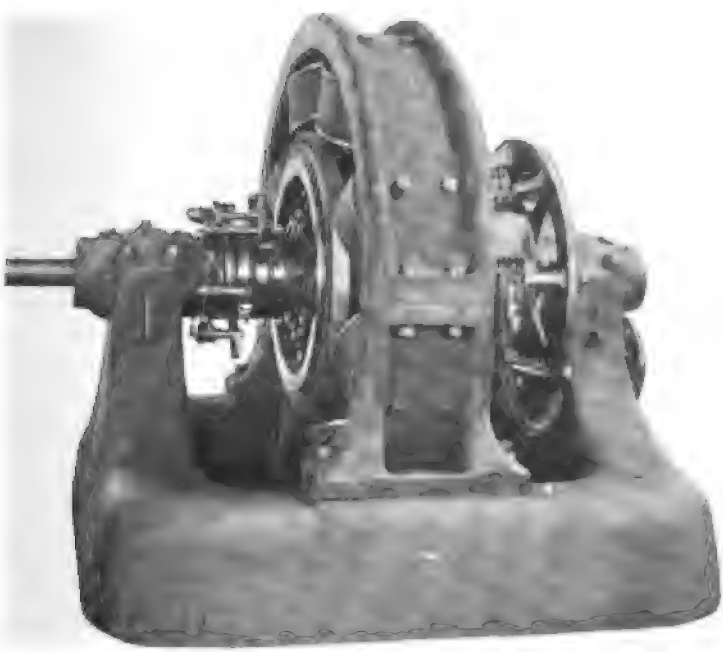


FIG. 148.

Plate III., shows a 250 KW Westinghouse diphase machine, for about the same frequency. A number of these machines have been fitted with pulleys and used as double-ended generators in connection with railway work. The monophase form of this very interesting apparatus has not yet come into much practical use, not through any inherent faults, but because most of the power transmission has so far been accomplished with diphase and triphase currents.

The efficiency of these machines is, as might be expected from their character, practically the same as ordinary continuous current dynamos of the same output, or rather better





on account of shorter average path for the current in the armature. In fact, so far as general properties go, they are dynamos. They furnish at present by far the most available means of deriving continuous from alternating currents, for they are simple, of great efficiency, and of about the same price as other generators of the same capacity. In consequence they are coming into considerable use, save where dynamos are already available and only need a motor to drive them.

And yet the simplicity of the rotary transformer is attained at the cost of certain practical inconveniences that cannot lightly be passed by. Their source is the employment of a single field and armature winding for all the purposes of the apparatus. The results are, first, complete interdependence of the alternating and continuous voltages, and, second, consequent difficulties of regulation that are occasionally quite troublesome.

The immediate result of a single winding is that there is an approximately fixed ratio between the alternating and the continuous voltage. The former is always the less, and while varied by changes in the number of phases determined by the connections, is approximately the alternating voltage that would be yielded by the machine driven as a generator. This is, for monophase or diphase connections, about seven-tenths of the continuous current voltage, and for three-phase connections about six-tenths. The proportions would approximate to $\frac{1}{\sqrt{2}}$ and $\frac{\sqrt{3}}{2\sqrt{2}}$ respectively, if the alternating E. M. Fs. were sine waves, which they never are when derived from an ordinary continuous current armature. In service the real proportions may, and generally do, vary by several per cent. In a particular two-phase case the actual ratio was .68, and in a three-phase case .65. If, therefore, a rotary transformer be used for supplying continuous current, the applied alternating current must be of lower pressure than the derived continuous, in about the proportion above noted. This compels the use of reducing transformers in every case of power transmission involving this apparatus. Further, any cause that affects the alternating pressure affects the continuous as well. Line loss, inductance, resonance effects, as well as changes at the generators, all influence the voltage at the continuous current end

of the rotary transformer. Nor can this voltage be freely altered by changing the field strength of the rotary transformer, since as we have already seen this may profoundly change the inductance of the alternating circuit, which is for many reasons undesirable. Therefore compound winding, while perfectly practicable, may cause trouble. The best results are obtained by carefully adjusting the generator, line, and rotary transformer to work together. Otherwise there is very likely to be trouble in regulation.

For these reasons in cases where close regulation is necessary, as for incandescent lighting, preference has frequently been given to the motor generator with double field and armature, as in the large Budapest plant installed by Schuckert & Co., who were among the pioneers in developing the rotary transformer. In this case the transmission is at 2,000 volts diphase, at which pressure current is delivered to the motor end of the motor generators placed in sub-stations at convenient points. In such a plant the increased cost of the duplex machines is not so great as might be supposed, for reducing transformers are needless, and the output of both generators and motors can be forced to the utmost limit of efficient operation, without fear of injuring the regulation, which is reduced to the easy problem of accurately compounding a continuous current generator. The net efficiency of the Budapest transformation is said to be 85 per cent. Like double-wound dynamotors, rotary transformers are limited in practicable frequency. They are quite difficult to build in large sizes for more than 40~, and become really easy and cheap of construction in the neighborhood of 30~ or below.

From the foregoing it is sufficiently evident that every case of current reorganization cannot be successfully met by the same apparatus. For arc lighting the rotating commutator seems to be very well suited, and for that purpose it is cheaper and more efficient than any of its rivals. Next in point of efficiency and cheapness comes the rotary transformer, infinitely better for heavy work than any commutating device, and finding already extensive application to electric railway work. Finally for work requiring very close regulation, the motor generator is specially well suited, closer to the rotary transformer in cost and efficiency than would be supposed offhand,

and unique in the complete independence of its working circuits.

Practice in this line of operations has not yet settled into fixed directions, and is not likely so to do just at present. Each plant must therefore be considered by itself and treated symptomatically.

American usage is at present tending strongly toward the rotary transformer, on account of its ready adaptation to railway service, but in view of the work that has been done on alternating motors for such service, it is an open question how far current reorganization will be generally necessary in the future, and what apparatus will be best suited to those cases in which it may prove to be desirable.

CHAPTER VII.

PRIME MOVERS.

MECHANISMS that constitute the link between natural sources of energy and mechanical power are called prime movers. So far as the electrical transmission of energy is concerned, but two classes of prime movers, steam engines and water-wheels, have to be seriously considered. All others sink into insignificance or are limited to special and rarely-occurring cases. When power is transmitted electrically over considerable distances the prime mover is usually a water-wheel, since, as yet, the transmission of power from coal fields has been hardly more than proposed, although when long electrical lines become somewhat more familiar, coal may become a frequent source of energy. Where the distribution of power from a central point is to be accomplished, the prime mover is frequently a steam engine.

The general principle of the steam engine may be fairly supposed to be somewhat familiar to the reader, but the conditions of economy are not always so clearly understood. The source of power in an engine is the pressure of the steam, which must be utilized as fully as possible to get anything like efficient working. Since the pressure is in direct proportion to the temperature in any gas, the proportion of the total pressure which can be used depends on the original temperature at which its use is begun, and the temperature at which one ceases to use it and rejects it together with all the energy it then possesses. These temperatures are not to be reckoned from the ordinary zero of a thermometer, but from the so-called absolute zero. This is that point from which, if the temperature of a gas be reckoned, its pressure will be directly proportional to the temperature. It is 461° below zero, Fahrenheit, that is, 493° below the melting point of ice. It is determined by the consideration that any gas at this melting point loses $\frac{1}{493}$ of its pressure for a change in temperature of

one degree, hence if it could be cooled down 493°, would lose its pressure and would have given up all of its energy. Counting from this absolute zero then, one can utilize that part of the whole energy of a gas which lies between the temperature at which the gas begins to work and that at which it ceases to do work. In other words the efficiency of any engine operated by gaseous pressure is:

$$\frac{T_1 - T_2}{T_1}$$

In which T_1 is the absolute temperature of the gas when it begins to do work in the engine, and T_2 the absolute temperature at which its work ends. In practice T_1 is the temperature of the steam when it enters the cylinder, and T_2 the temperature of exhaust or condensation. Steam permits the use of but a limited range of temperature on account of the temperature at which it liquefies, and bothers us by condensing as it expands, even in the cylinder. It must be remembered that while we are limited by our possible range of temperature to a low total efficiency in any heat engine, of the energy that can possibly be obtained within this limitation, a very good proportion is recovered in the best modern engines—from one-half to two-thirds. The remainder is lost in various ways, largely through radiation of heat and cylinder condensation. Besides these thermal losses a portion of the energy utilized is wasted in friction of the mechanism.

From these considerations we may derive the following general principles of engine efficiency:

I. The steam should be admitted at the highest pressure feasible and exhausted at the lowest pressure possible.

This indicates that high boiler pressure should be used, and that it is better to condense the steam than to expel it into the air, as by condensing most of the atmospheric pressure can be added to the working range of pressure in the engine. In the next place it is evident that the steam should be sent into the engine at full boiler pressure, and finally condensed after expanding and yielding up its pressure as completely as possible.

II. Waste of heat in the engine should be stopped as far as possible. This means checking losses from the cylinder by radiation and conduction, and internal loss from cylinder

condensation. The first principle laid down has for its object the increase of the possible efficiency, while this second principle bears on the securing of as large a proportion as possible of this possible efficiency. It requires the prevention of escape of heat externally by protecting the cylinder, and incidentally shows the advantage of high pressure and high piston speed in securing as much work as possible without increasing the size of the working parts, and hence their chance for radiation. On the other hand it indicates the danger of working with too great a range of temperature in the cylinder, thus producing cylinder condensation.

III. The work of the engine should be the maximum practicable for its dimensions and use. This secures high mechanical efficiency as the previous principles secure high thermal efficiency. To fulfill this condition high steam pressure and high piston speed are necessary, and the latter usually means also rather high rotative speed. The importance, too, of fine workmanship in the moving parts is evident.

It will be realized that some of the conditions just pointed out are mutually incompatible to a certain extent. Everything points, however, to the great desirability of a condensing engine, worked with a high initial steam pressure and great piston speed. The tendency of the best modern practice is all in this direction, and the efficiency of engines is constantly improving. The greatest advances of the past decade or two have been in the introduction of compound engines. The principle here involved is the lessening of thermal losses in the cylinder by avoiding extremes of temperature between the initial and the final temperature of the steam expanded into it. Compound engines simply divide the expansion of the steam between two or more cylinders, so that the temperature range in each is limited, without limiting the total amount of expansion.

Following the same line of improvement, triple and quadruple expansion engines are becoming rather common, although the value of the last mentioned is somewhat problematical at present.

For practical purposes steam engines may be classified in terms of their properties, somewhat as follows:

First, there is the broad distinction between condensing and

non-condensing engines. The former condense the exhausted steam and gain thereby a large proportion of the atmospheric pressure against which the latter class is obliged to do work in exhausting the steam. Where economy of operation is seriously considered, the non-condensing engine has no place, if water for condensation is obtainable.

Each of these classes falls naturally into sub-classes, depending on the number of steps into which the expansion is divided—simple, compound, triple expansion, etc. Of these the first may now and then be desirable, where the size is small and coal very cheap, but for the general distribution of energy the last two are more generally useful. Furthermore each of the sub-classes mentioned may be divided into two genera, depending on the nature of the valve motions that control the admission and rejection of the steam. To follow out the first principle of economy laid down, the steam must be admitted at a uniform pressure as near that of the boiler as possible, the admission should be stopped short after entrance of enough steam for the work of the stroke, the steam allowed to expand the required amount, and then rejected completely at the lowest possible pressure. The admission valves should therefore open wide and very rapidly, let in the steam for such part of the stroke as is necessary, and then as promptly close. The exhaust valves should open quickly and wide when the expansion is complete, and stay open until nearly the end of the stroke, closing just soon enough to cushion the piston at the end of its stroke. In proportion to the completeness with which these conditions are met the use of the steam will be economical or wasteful. The two genera of engines referred to are those in which the motions of the admission and exhaust valves are independent of each other or dependent. Fig. 149 shows in section the cylinder and valves of an independent valve engine, Corliss type. The arrows show the flow of the steam. The admission valve on the head end of the cylinder has just been opened, as also has the exhaust valve on the crank end.

The essential point of the mechanism is that the admission valves open and close at whatever time is determined by the action of the governor without in the least affecting the working of the exhaust valves. In the Corliss valve gear the steam valves are closed by gravity, or by a vacuum pot, and

are opened by catches moved by an eccentric rod, and released at a point determined by the governor, which thus varies the point of cut-off according to the load. Ordinarily the admission of steam is thus cut off in a simple engine at full load after the piston has traversed from one-fifth to one-quarter of its stroke, according to the pressure of the steam. If the cut-off is too late in the stroke, there is not sufficient expansion of the steam ; if too early the steam is partially condensed by too great expansion. For every initial pressure of steam there is a particular degree of expansion which gives the best results in a given engine.

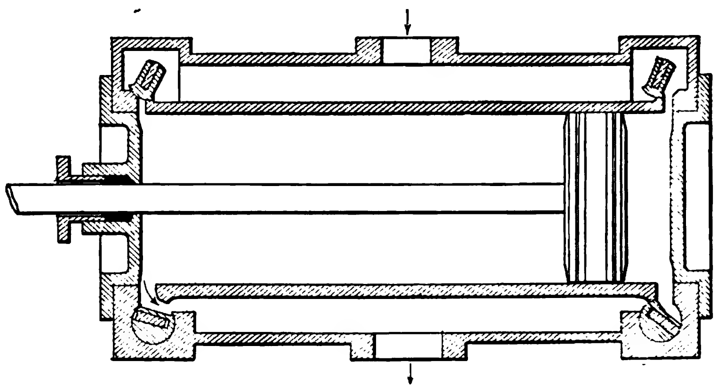


FIG. 149.

Fig. 150 shows the valve motion of one of the best of the dependent-valve genus. Steam is just being admitted at the head end both around the shoulder of the hollow piston valve and through the ports at the other end of the valve *via* the interior space. At the crank end the exhaust port has just been fully opened. It will be seen that any change in the conditions of admission also involves a change in the conditions of exhaust, and although some variation may take place in the latter without serious result on the economy, simplicity in the valve gear has been gained at a certain sacrifice of efficiency in using the steam. Both independent and dependent valve engines have many species differing widely in mechanism, but retaining the same fundamental difference. Of the two genera, the independent-valve engine has the material advantage in efficiency, and under similar conditions

of pressure, capacity, and piston speed consumes from 10 to 20 per cent. less steam for the same effective power. It therefore is generally employed in spite of somewhat greater first cost, for all large work, often in the compound or triple-expansion form. Except in small powers, or for exceptionally high speed, the dependent-valve engine has few advantages, and in the generation of power on a large scale, such as for the most part concerns us in electrical transmission work, it hardly has an important place.

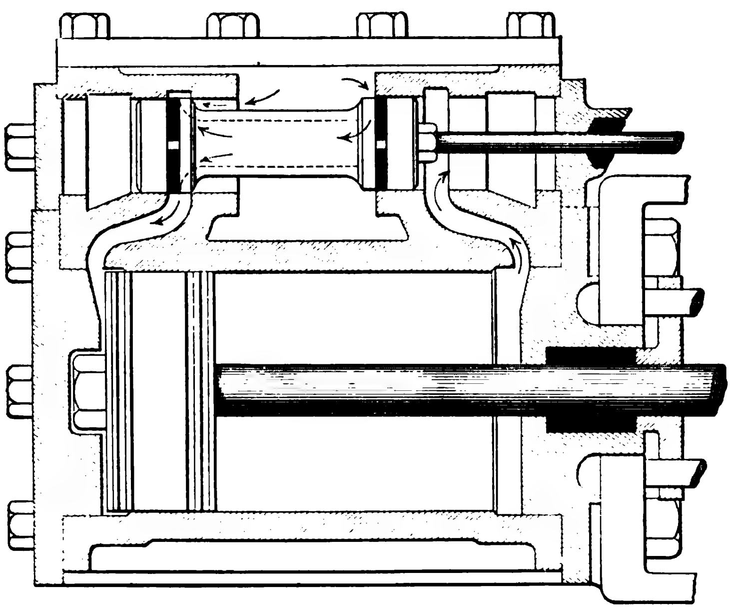


FIG. 150.

It must not be supposed that between the various sorts of engines mentioned there are hard and fast lines. In the economical use of steam a very large non-condensing engine may surpass a smaller condensing one, or a fast running dependent-valve engine, a very slow running one with independent valves. Broadly, however, we may lay down the following propositions concerning engines of similar capacity:

I. Condensing engines will always furnish power more economically than non-condensing ones. This is particularly

true at less than full load, since the loss of the atmospheric pressure may be taken as a constant source of inefficiency, which, like mechanical friction, is very serious at low loads. For example, a triple-expansion engine working at one-quarter load in indicated HP, will be likely to have its consumption of steam per IHP, increased from 15 to 25 per cent. above the consumption per IHP at full load; while worked non-condensing, the increase would be from 50 to 100 per cent. Hence for electrical working where light loads are frequent, condensing engines are an enormous advantage. With simple or compound engines the same general rule holds good as for triple-expansion engines, with the additional point that light loads affect their economy even more, when worked non-condensing. It must be borne in mind that if any engine is to do its best under varying loads, its valve gear and working pressure must be arranged with this in mind, else the advantage of high expansion and condensing may be thrown away. It is frequently said that triple-expansion engines do not give good results in electric railway work. When this is the case there has been improper adjustment of engine to load.

II. Among engines having the same class of valve gear, compound engines give better economy than simple ones, and triple-expansion better than compound. This is true irrespective of the nature of the load, supposing each engine to be suitably adjusted to the work it has to do. In rare cases, owing to exceedingly cheap fuel and short working hours, it may happen that the advantage of a triple-expansion engine over a compound in economy of coal may be more than offset by increased interest on investment, but at the present cost of engines and boilers, this could not well occur unless in the case of burning culm or poor coal obtained at a nominal price.

III. As regards speed of engines, there is always advantage in high piston speed both as respects first cost and mechanical efficiency. So far as the economical use of steam goes, speed makes little difference save as it sometimes involves a change in the valve gear. Most high-speed engines have valve gear of the dependent sort, which puts them at a disadvantage except in so far as lessened cylinder condensation and friction may offset the losses due to less efficient distribution of the

steam. But the best dependent-valve engine is uniformly less economical than the best independent-valve engine of the same class and sub-class. Even the lessened friction of the small high-speed pistons does not offset this difference in intrinsic economy.

As regards actual economy in the steam consumption, the size of engine has a powerful though somewhat indeterminate influence. Even at full load, simple non-condensing dependent-valve engines of moderate size require from 30 to 40 lbs. of steam per indicated horse-power-hour. Only in very large engines, such as locomotives, and specially fast running engines such as the Willans, does the steam consumption of these dependent-valve engines fall below 30 lbs., and not very often even in these cases. Worked condensing the same machines use from 20 lbs. in exceedingly favorable cases to 25 or 30 lbs. more commonly.

Independent valve engines, simple and non-condensing, will give the indicated HPH on 25 to 30 lbs. of steam, occasionally on as little as 22 to 23 lbs. With the advantage of condensation these figures may be reduced to say 18 to 25 lbs., the former figure being somewhat exceptional and probably very rarely attained in practice.

Passing now to compound non-condensing engines, the effect of compounding on efficiency is about the same as that of condensing. Ordinary dependent-valve engines of compound construction require from 20 to 28 or 30 lbs. of steam per IHP hour. The former result is very exceptional, and seldom or never reached in practice, while the last-mentioned would be considered rather high. Independent-valve compound engines are so seldom worked non-condensing, that the data of their performance are rather meagre; 18 to 25 lbs. of steam is about the usual amount, however.

When condensation is employed, on the other hand, the dependent-valve engines are in rather infrequent use. When the need for economy is so felt as to lead to the use of compound engines, it also leads to the use of economical valve gear. The steam consumption of dependent-valve compound-condensing engines is quite well known, however, and is usually from 16 to 24 lbs. per IHP hour. The first mentioned figure is rarely reached, and only in special types of engine.

Plenty of tests on compound condensing engines with independent valves are available; 14 to 20 lbs. of steam covers the majority of results. Occasional tests run as low as 13 and as high as 22 lbs.

It is noticeable that in compound engines the difference between dependent and independent valve gear is less than with simple engines. This is due to a variety of causes. The larger range of expansion used in compound engines tends to lessen the deleterious effects of moderate variations in the distribution of the steam, and besides, the valve gear of compound engines is not infrequently composite, the high-pressure cylinder having independent valves and the low-pressure cylinder dependent ones.

The same arrangement is often used in triple-expansion engines, so that, in conjunction with the condition before mentioned, it is usually true that the economy of dependent-valve triple-expansion engines is much nearer that of independent-valve ones than would be at first supposed. Without condensing a dependent-valve triple-expansion engine may be expected to require from 19 to 27 lbs. of steam per IHP hour. With condensation such engines perform much better, the steam consumption being reduced to 14 to 20 lbs.

Nearly all triple-expansion engines, however, are built with independent valves at least in part, the intention being to secure the most economical performance possible. Under favorable conditions their steam consumption runs as low as 12 lbs. per IHP hour, and seldom rises above 18 lbs. In a few exceptional cases the record has been reduced slightly below 12 lbs., but such results cannot fairly be expected. Anything under 13 lbs. of steam per HP is exceedingly good practice for running conditions.

All the figures given refer in the main to good-sized engines of at least 200 HP and over, operated at full load and at favorable ratios of expansion. It must be clearly understood that there is for each steam pressure a particular ratio of expansion which will give the most economical result—less expansion than this rejects the steam at too high a temperature; more, causes loss by condensation, etc. Compound and triple-expansion engines permit greater expansion of the steam without loss of economy, hence allow higher steam pressure and a

greater temperature range—hence higher thermal efficiency. Good practice indicates that for simple engines the boiler pressure should be not less than 90 to 100 lbs. per square inch, for compound engines not less than 110 to 120, and for triple-expansion engines not less than 140 to 150, and thence up to 175 or 200 lbs.

We may gather the facts regarding steam consumption into tabular form somewhat as follows:

Kind of Engine.	Steam per IHP. General Range.	Steam per IHP. Working Average.
Simple, non-con. dep. v........	30–40	33
" " indep. v......	25–30	28
" con. dep. v......	20–30	25
" " indep. v..........	18–25	21
Compound, non-con. dep. v....	20–28	24
" " indep. v...	18–25	22
" con. dep. v	16–24	20
" " indep. v......	14–20	18
Triple, con. dep. v............	14–20	17
" " indep. v	12-18	15
"large," "	12-14	13

The engines considered are supposed to be of good size—say 200 to 500 HP, and to be worked steadily at or near full load. The figures given as working average are such as may be safely counted on with good engines, kept in the best working condition, and operated at at least the boiler pressures indicated. The steam is supposed to be practically dry and the piping so protected as to lose little by condensation. These results are such as may regularly be obtained in practice, and indeed it is not uncommon to find them excelled. Compound-condensing engines of large size not infrequently work down to 17 pounds of steam, and triple-expansion condensing down to 14 pounds, which result will be guaranteed by most responsible builders.

Unfortunately engines employed for electrical work are comparatively seldom kept at uniform and full load. Furthermore, they are subject to all sorts of variations. In electric railway service there are sudden changes from light loads to very heavy ones, while in electric lighting there is generally a gradual increase to the maximum load, which continues an hour or two,

followed by a rather gradual decrease. These variations affect the economy of the engines unfavorably—at certain loads there is not enough expansion, at others decidedly too much. The variations in economy are largely controlled by the proportioning of the engine to its work. To say that an engine is of 500 HP, means little unless the statement be coupled with a definite explanation of the circumstances. If that output is obtained by admitting steam for half the stroke, the engine will work at 500 HP very uneconomically, supposing a simple engine to be under consideration. Its point of maximum economy may be perhaps 300 HP. On the other hand 500 HP may be given when cutting off the steam at one-fifth stroke. In this case the engine will be working near its point of maximum economy, and at 300 HP will require much more steam per IHP. It could give probably 600 to 700 HP at a longer cut-off, and is really a much more powerful engine than the first. For uniformity it is better to rate an engine at the HP of maximum economy, whatever the real load may be. The relation of load to economy is well shown in the curves of Fig. 151.

Curves 1, 2, 4, and 5, are of engines so rated as to have their maximum economy near full load. Curve 3, on the other hand, is from an engine intended to give its highest economy at about three-quarters load. For very variable output this is the preferable arrangement, while for large central station work, when the number of units is large enough to permit loading fully all that are running at any one time, it is better to have each unit give its very best economy near full load and to vary the number of units according to the requirements of total load.

For electric railway service under ordinary conditions, it is best to employ an engine which at full load is worked to a high capacity, and hence somewhat uneconomically, while at lesser loads, which more nearly correspond with the average conditions, its economy will be at a maximum. For electric lighting service it is preferable to have the point of maximum economy fall more nearly at full load. For power service, which is on the one hand more uniform than railway service, and less uniform than electric lighting work, it is probably best to employ an engine having characteristics between those just

mentioned. In every case attention must be paid to the character of the load as regards average amount and constancy in the choice of an appropriate engine for the work. In cases where the variations of load are likely to be very sudden, great mechanical strength of all the moving parts is

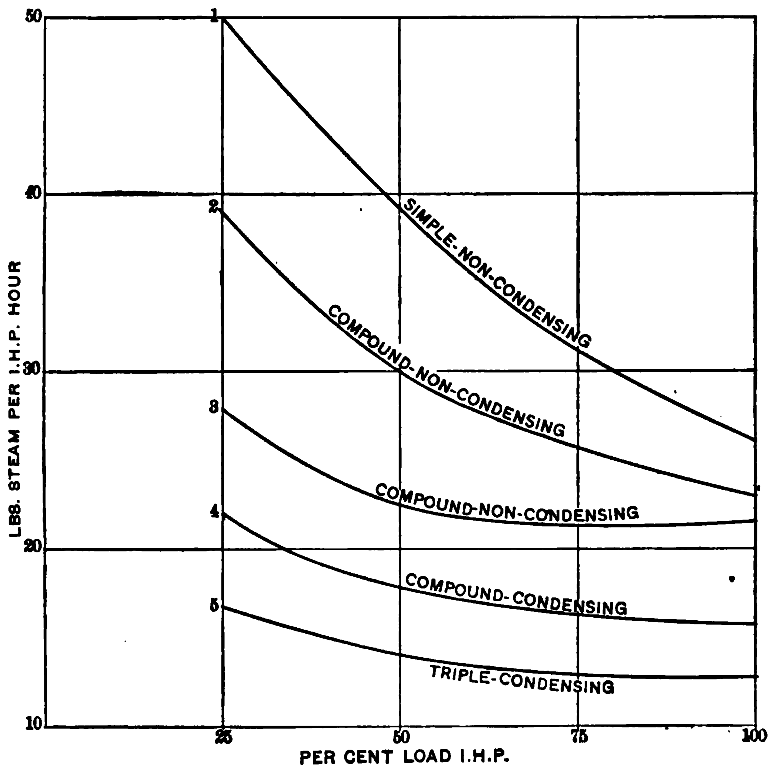


FIG. 151.

absolutely necessary, and an attempt should be made in planning the power station to arrange the engine for its best economy at average load as nearly as this can be predicted.

Many blunders are made by being too hasty in buying engines for electric service, and not sufficiently studying the problem. For uniform loads the selection of the engines can be made easily. For variable loads it requires great astuteness and experience, nor is it safe to argue from experience

based on other kinds of variable service. No engines can be subject to greater variations of load than are met in marine engines driving a ship in a high sea. If the screw rises from the water the whole load is thrown off, and resumed again with terrible violence when the screw is submerged. Nevertheless an engine, which is so arranged as to perform well under these trying circumstances, might perform badly when put on electric railway or power service, not because of its inability to stand the far less severe changes of load, but for the reason that the average load would be much further from its full capacity than in the case of marine practice. For large railway and power service it is best to use direct connected units for the sake of compactness and economy. If a station is of sufficient magnitude to employ four or five 500 HP engines, direct connecting is advisable in nearly every case.

It has been said that such a plant has a lack of flexibility, that is dangerous in case of sudden and great variations of load. This is not true if the engines have been intelligently proportioned for the work they have to do, although in some cases there has been trouble due to the fact that the engines were ill-fitted to operate successfully under the changes of load to which they were subjected. As a matter of economy both in engines and dynamos, it is desirable to work direct coupled plants at a fairly high speed. There is no need of exaggerating the size of both engine and dynamo for the sake of running at 50 to 70 revolutions per minute, when equally good engines and dynamos of smaller size and less weight can be obtained by running at 100 or 120 revolutions or more. Much of the unwieldiness charged against large direct-coupled units has been the result of yielding to the importunities of some engine builder, who wants to sell a very large machine, and putting in an engine and dynamo which run at absurdly and unnecessarily low speed.

Electric power transmission, with a steam engine as the prime mover, is most likely to be developed in the direction of very large plants, to which these remarks apply most forcibly, particularly as in order to make transmission of power from a steam-operated station profitable, it is necessary to seek the very highest efficiency. Apart from the cost and inconvenience of very low speed units, it must be borne in mind that the

mechanical efficiency of large low speed engines with heavy pistons and enormous fly-wheels is lower than that of those designed for more reasonable speeds, which gives added reason for moderation in planning direct-coupled units.

Throughout the design of a power station the probability of light loads must be considered. Not only does this have an important bearing on the economy of the engines, but it influences that of the boilers as well. The cost of operation depends on the coal consumption, and this in turn not only on the amount of steam that must be produced, but on the efficiency of its production.

There is, however, no classification of boilers on which one can safely rest in judging of their economy. There is much more difference in economy between a carefully fired and a

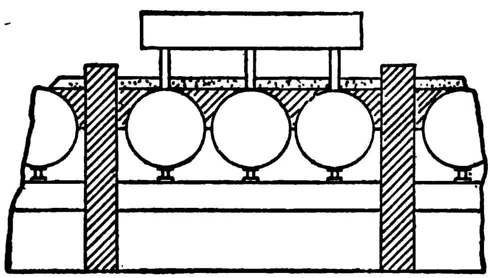


FIG. 152.

badly fired boiler of the same kind, than there is between the best and the worst type of boiler in ordinary use. Boilers may be generally divided into three classes: Shell boilers, in which the water is contained in a plain cylindrical tank heated on the outside; tubular boilers, in which there are one or many tubes running lengthwise of the boiler shell, and serving as channels for the heated gases from the fire; and water-tube boilers, in which the water is contained in a group of metallic tubes, around which the heat of the fire freely plays. Fig. 152 shows a cross-section through the furnace of a bank of boilers of the first class. In this case, three shells were placed over each furnace communicating with a common steam drum. Each shell was 30″ in diameter and 30′ long. Fig. 153 represents one of the many forms of tubular boiler. In this the structure is vertical, with a furnace at the bottom, and the

tubes are numerous and rather small, giving a large heating surface. Tubular boilers are very often arranged horizontally, and in one very excellent and common type (return tubular),

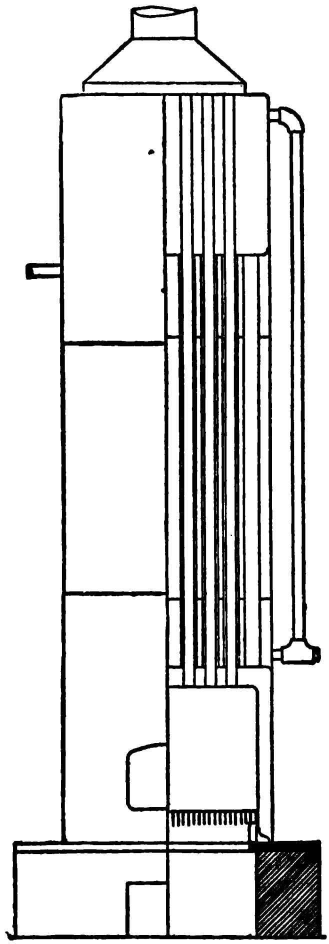


FIG. 153.

the flame and heated gases pass horizontally under the boiler shell and then back through the tubes to the furnace end and thence upward into the stack. A typical water-tube boiler is shown in Fig. 154. Here the furnace is at the right

of the cut and the stack at the left. The tubes are inclined as is usual in water-tube boilers, and steam space is secured by the drum above. Each class of boiler has nearly as many modifications as there are makers, most of them being with relation to the arrangement of the fire with respect to the boiler proper.

As to the merits of the different classes, opinions differ very widely. It is clear from experience that the simple shell boiler is decidedly inferior to either of the others in economy, in spite of its simplicity and cheapness. Of late years it

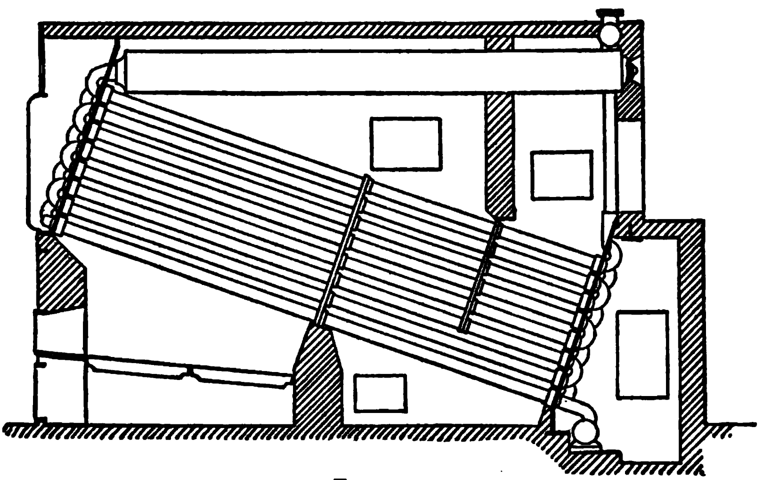


FIG. 154.

has been the fashion to employ water-tube boilers under all sorts of conditions, on account of their supposed great efficiency as steam producers, safety and compactness. Purely experimental runs with such boilers often show phenomenal efficiency, but tests under working conditions sometimes result otherwise. It is important to note that not only does skill in firing produce a great improvement in boiler economy, but that by influencing the firing different kinds of coal give very different results quite independent of their theoretical value as fuel. The thermal value of coal, or other solid fuel, is almost directly as the proportion of carbon contained in it, and for comparative purposes boiler tests are generally reduced to evaporation of water from and at 212° F. per lb.

of combustible used, *i. e.*, per lb. of carbon. However, the firing in different furnaces is differently affected by changes in fuel, so that it is impossible to predict by tests on one boiler what a similar one will do under other conditions.

Altogether, the subject of boiler efficiency is a difficult and tangled one, since the conditions are constantly changing, and the best guide is found in the general result of a long series of tests rather than in theories of combustion. Forcing the output of a boiler usually injures its efficiency by compelling the combustion of an abnormal amount of coal for the grate surface of the furnace. It follows that a boiler is apt to be more efficient at moderate loads than at very high ones. As this is the reverse of what happens in an engine, it might be supposed that the boiler could partially compensate for engine inefficiency, but on the contrary inefficient production of steam is anywhere and always a bad thing in itself, and only to be tolerated for some very good reason. In marine practice, boilers may sometimes have to be forced to a high output to save weight and space. In electric stations it is sometimes better to force the boilers at the hours of heavy load, than to keep a relay of boilers banked in readiness for use, but except for this, the boilers, like the rest of the plant, should be worked as near their maximum efficiency as possible.

The best fuel to use is not at all invariably that of the highest thermal value, in fact with the proper furnace a grade of coal only moderately good is very often the most economical. In starting a steam plant of any kind comparative tests of various coals should generally be made, and are more than likely to pay for themselves many times over. In absolute heating value various kinds of fuel compare about as follows:

Kind of Fuel.	Heat of Combustion.	Evaporation.
Best anthracite	15,250	15.8
Welsh steam coal	14,500	15.0
Pocahontas	14,375	14.9
Cumberland	13,750	14.2
Coke, ordinary	12,750	13.2
Cape Breton	12,500	13.0
Lignite	11,750	12.2
Peat, dry	9,650	10.0
Wood, dry	7,250	7.5

The heat of combustion is per lb. of fuel, and is given in thermal units, this unit being the heat required to raise 1 lb. of water 1° F.

The evaporation gives the pounds of water which can be evaporated from and at 212° F. by the complete utilization of the annexed heats of combustion. In other words no more than 15 lbs. of water can possibly be evaporated by 1 lb. of coal of the thermal value of 14,500. Extravagant claims are sometimes made for patented boilers of strange and unusual kinds, so it is well to bear these figures in mind and to remember that you cannot evaporate more water than the figures indicate, any more than you can draw a gallon out of a quart bottle. In practice coal is likely to fall perhaps 10 per cent. below the thermal values given above. Good boilers with careful firing will utilize from 60 to 75 per cent. of the thermal value of the coal. Occasional experimental runs may give slightly higher figures, but only under very exceptional circumstances.

Now as to actual tests under boilers. Examinations of more than a hundred carefully conducted tests by various authorities show from 8 to 13 lbs. of water evaporated from and at 212° per lb. of combustible. As average good steam coal contains from 10 to 15 per cent. of ash, these results correspond to from 7 to 11¾ lbs. of water evaporated per lb. of coal. Now and then a single test gives a result a few hundredths of a pound better than 13 lbs. per lb. of combustible, and an occasional poor boiler shows less than 8 lbs. Generally from 10 to 15 lbs. of coal are consumed per hour per square foot of grate surface. The following table gives a general idea of the results of boiler tests, good, bad, and indifferent.

The evaporation is per lb. of combustible. The most striking feature of this table is the small difference in efficiency between the various kinds of boiler. Putting aside the cylindrical shell boilers, which are distinctly inferior to the others, it appears that as to the other types of boiler there is little to choose on the score of economy. The difference between the better and worse boilers of each class, due to difference of design, condition, and firing, is much greater than the difference between any two classes. Even the same boiler with

different fuel, firing, or when in different conditions, may give evaporative results varying by 25 per cent. Economy depends vastly more on careful firing and proper proportioning of the grate and heating surfaces to the fuel used, than upon the kind of boiler. In fact, judging from all the available tests the differences between various types of boiler are quite small.

KIND OF BOILER.	KIND OF COAL.	EVAPORATION.
Return tubular	Welsh steam	13.12
Water-tube	Bituminous, 3 parts; pea and dust, 1 part	13.01
Return tubular	Cumberland	12.47
Vertical "	"	12.29
Return "	"	12.07
" "	"	12.03
" "	Anthracite	11.63
Marine	Newcastle	11.44
Water-tube	Anthracite	11.31
" "	Cumberland	10.98
Plain tubular	Anthracite	10.88
Water-tube	Cumberland	10.79
Marine	Welsh steam	10.44
Return tubular	Anthracite	10.43
Locomotive	Coke	10.39
Water-tube	Anthracite	10.00
Return tubular	"	9.55
Cylinder	"	9.22
"	Cumberland	8.74
"	Anthracite	8.44

The most that can be said is that plain shell boilers are somewhat inferior to the other forms, of which the horizontal return tubular and the water-tube have given slightly higher results than the others. Water-tube boilers are generally rather lighter and stand forcing better than ordinary tubular boilers. They also are less likely to produce disastrous results if they explode. On the other hand they are more expensive, and are as a class hard to keep in good condition.

Probably under average conditions a well-designed horizontal return tubular boiler will give as great evaporative efficiency as can be attained in service, and the choice between it and a water-tube boiler is chiefly in economy of space and capacity for forcing. There is no excuse for the explosion of any properly cared for boiler.

The actual evaporation secured per lb. of total fuel is something quite different from the figures in the table just given. In the first place allowance must be made for ash and fuel used for banking the fires. In the second place in regular running the firing is seldom as careful as in tests.

On account of these the evaporations per lb. of combustible given in the table must be reduced from 15 to 20 per cent. to correct the result to pounds of coal used in actual service.

Ten lbs. of water or over evaporated from and at 212° per lb. of total fuel may be regarded as exceptionally good practice in every-day work. Nine to 10 lbs. under the same conditions represents fine average results, and 8 to 9 lbs. is much more common. In fact 8 lbs. is an unpleasantly frequent figure, particularly in boilers operated under variable load, such as is generally found in electric plants of moderate size. All these facts point out the necessity of thorough and careful work in every part of a power plant. Bad design or careless operation anywhere plays havoc with economy.

Reverting now to engine performances, we may form a fairly definite idea of what may be expected in the way of coal consumption per indicated horse-power hour.

The following table shows the coal consumption of the various kinds of engines, based on the burning of 1 lb. of coal for each 9 lbs. of feed water used. Although greater evaporation can often be obtained, 9 lbs. of water per lb. of coal is a very good performance indeed, decidedly better than is found in general experience. It presupposes good boilers, good coal, and skillful firing, such as one has a right to expect in a large power plant.

Kind of Engine.	Coal per IHP Hour.	
	Condensing.	Non-condensing.
Simple, dependent valve	2.77	3.66
" independent valve	2.33	3.11
Compound, dependent valve	2.22	2.66
" independent valve	2.00	2.44
Triple, dependent valve	1.88	
" independent valve	1.66	
" " " large	1.44	

The figures apply only to engines of several hundred HP, at or near their points of maximum economy and operated from a first-class boiler plant.

They can be and are reached in regular working, and are sometimes exceeded. A combination of great efficiency at the boilers and small steam consumption in the engine sometimes gives remarkable results. The best triple-expansion condensing engines worked under favorable conditions can be counted on to do a little better than 1.5 lbs. of coal per IHP hour, occasionally even in the neighborhood of 1.25 lbs. Even with compound condensing engines tests are now and then recorded, showing below 1.75 lbs. of coal per IHP hour. But these very low figures are the result of the concurrence of divers very favorable conditions, and those just tabulated are as good as one really has the right to expect. It must not be supposed that the weight of coal used per HP hour necessarily determines the economy of the plant. The cost of fuel of course varies greatly, and its price in the market is by no means proportional to its thermal value. As a rule the coals which give the best economic results are not those of the greatest intrinsic heating power. On the contrary, dollar for dollar, the best results are very frequently obtained from cheap coal, or mixtures of inferior coal with a portion of a better grade. Hence the boilers of a plant which is a model of economy may show an evaporation of only 6 or 7 lbs. of water per lb. of coal. Boiler tests with the conditions of economy in view are of great importance and are likely to pay for themselves tenfold in even a few months of operation.

A word here about fuel oil. Petroleum has, weight for weight, much greater heating power than coal. Its heat of combustion is about 20,000 to 21,000 thermal units, it costs little to handle and fire, leaves no ash and refuse to be taken care of, produces little smoke, and is generally cleanly and convenient.

It has been thoroughly tried by some of the largest electrical companies in this country, and at moderate prices, a dollar a barrel or less, is capable of competing on fairly even terms with coal. But experience has shown some curious facts about its performance. The amount of steam or equiva-

lent power required to inject and vaporize the oil in one of the most skillfully handled plants in existence amounts to no less than 7½ per cent. of the total steam produced. And curiously enough, the cost of oil for firing up a fresh boiler, and the time consumed, compare unfavorably with the results obtained from coal. In spite of the great amount of heat evolved from fuel oil, it appears to be less effective in giving up this heat to the boiler by radiation and convection. There is good reason to believe that more than half the total heat of combustion of incandescent fuel is given off as radiant heat, and most of the remainder is of course transferred by convection both of heated particles of carbon and of molecules of gas.

It is not unlikely therefore that a petroleum fire with its small radiating power and comparative absence of incandescent particles, fails in economy through inability to give up its heat readily. This view of the case is borne out by the facts above cited and by the abnormally high temperature of the escaping gases often found in boiler tests with petroleum fuel. At all events it is clear from such tests that the evaporation obtained from fuel oil is not as great as would be expected from its immense heat of combustion, and unless at an exceptionally low price, its use is less economical than that of coal.

For an electrical power station operated by steam power the vital economical question is the cost of fuel per kilowatt hour, rather than the performance of engines and boilers alone. This final result involves the performance of the station apparatus under varying loads, too frequently rather light, and, implicitly, the skill of the operator in keeping his apparatus actually running as near its point of maximum economy as possible in spite of changes in the electrical output. This personal element forbids a reduction of the facts to general laws, but a concrete example will be of service in showing what may be expected in a well-designed and well-operated power plant. Fig. 155 shows a pair of "load lines," from a large and particularly well-operated power plant. The solid line shows the variations of load throughout a day in the latter end of January, and the broken line the variations of load during a day early in April.

The early darkness of a winter's day is very obvious in the

former line. The station carries in addition to lights a heavy motor service that keeps up a fairly uniform load throughout the day, until the sudden call for lights in the early evening. The load factor shown by the solid line is .35 (*i. e.*, this is the ratio between maximum and average load). The second load line gives a much better relation between these quantities, the load factor being .64, which is quite usual in

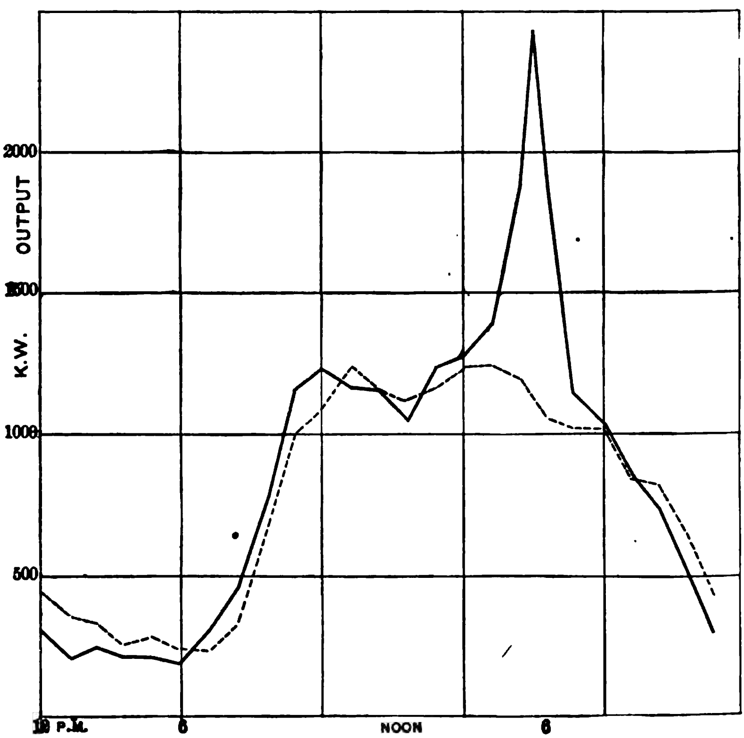


FIG. 155.

this station during the spring and summer. Of course every effort is exerted to keep the machines which are in use as fully loaded as possible. In spite of this the small output during the early morning hours, coupled with the losses due to circulating pumps and other minor machinery, and the fuel used for banking and starting fires, brings the cost of fuel during this period far above the average for the day. The curve in Fig.

156 shows roughly the variation in the cost of fuel per KW-hour throughout the day, taken from the average of a number of tests. As the fuel cost in a large central station is a considerable portion of the total expense, it is evident that the result is an excellent one. During all the hours of heavy load the cost of fuel is less than six-tenths of a cent per KW-hour, and the total cost of production but little more. This result will give an excellent idea of the cost of generating power on a large scale with cheap coal. It is, however, exceptionally good, and can only be equaled by a very well managed plant with the best modern equipment both electrical and mechanical.

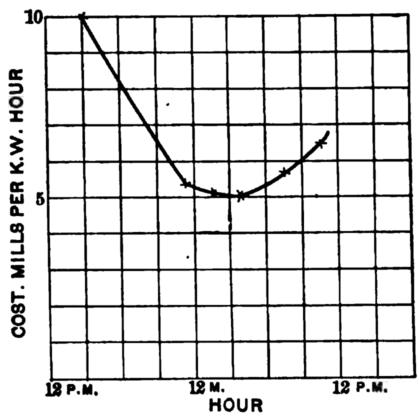


FIG. 156.

Of course the expenses of distribution, administration and the like must be taken into account in considering the cost per KW-hour delivered. The general question of station expenses cannot be here investigated, but this brief digression gives some idea of the necessary relation between the character of the work and the commercial results in generating electric power on a large scale, so far as the use of steam engines as prime movers is concerned.

The other grand division of prime movers, *i. e.*, water wheels of various classes, is the next subject for consideration.

The importance of the development of water powers for electrical purposes we have already come fully to realize. The lessons of the last few years have been exceedingly valuable

ones, and it is safe to say that the utilization of water power for electrical transmission will be kept up until every one which is capable of commercially successful development is worked to its utmost capacity. In spite of the length of time that water wheels of various sorts have been used, it is only very recently that these prime movers have been brought to a stage of development that renders them satisfactory for electrical purposes. The old water wheel was even more troublesome as a source of electrical power than the old slide valve steam engine.

The customary classification of water wheels for many years has been into overshot, undershot and breast wheels, and finally turbines. Various modifications of all these have, of course, been proposed and used Of these classes, the first three may be passed over completely as having no importance whatever in electrical matters, save in certain modifications so different from the original wheel as to be scarcely recognizable. To all intents and purposes they are never used for the purpose of driving dynamos, although occasionally an isolated instance appears on a very small scale.

It is the turbine water wheel which has made modern hydraulic developments possible, and more particularly electrical developments. The turbine practically dates from 1827, when Fourneyron installed the first examples in France, although it is somewhat interesting to know that an United States patent of 1804 shows a wheel of somewhat similar description, never so far as known used. The modern turbine consists of two distinct parts, the system of guide blades and the runner. The runner is the working part of the wheel, and consists of a series of curved buckets so shaped as to receive the water with as little shock as practicable, and to reject it only after having utilized substantially all of its energy. These buckets are arranged in almost every imaginable way around the axis of the runner, but always symmetrically.

Sometimes the curvature of the buckets is such that the water after having passed through them leaves the wheel parallel to its axis; sometimes so that the water flows inward and is discharged at the centre of the runner; sometimes so that it passes outward and is discharged at the periphery. More often the buckets have a double curvature so that the

water flows along the axis and at the same time either inwardly or outwardly. It is not unusual moreover to have two sets of buckets on the same shaft for various purposes. The growth of the art of turbine building has made any classification of turbines depending on the direction of the flow of the water very uncertain, as in nearly every American turbine this flow takes place in more than one general direction. Aside from the runner the essential feature of the modern turbine is the set of guide blades which surround the runner, and which are so curved as to deliver the water fairly to the buckets in such direction as will enable it to do the most good. Accordingly these blades are curved in all sorts of ways according to the way in which the water is intended to be utilized.

Fig. 157, taken from Rankine, shows a species of idealized turbine which discloses the principles very clearly. In this figure *A* is the guide blade system and *B* the runner. The flow is entirely along the axis, forming the so-called parallel flow turbine, a form not in general use in America.

Fig. 158 shows the sort of curvature which is given to the

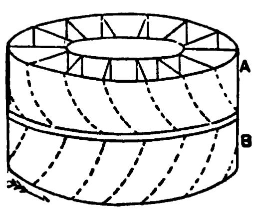


FIG. 157.

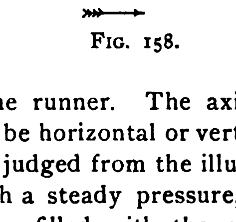


FIG. 158.

guide blades and to the buckets of the runner. The axis of this or any other kind of turbine may be horizontal or vertical, as convenience dictates. As may be judged from the illustration, the water acts on the runner with a steady pressure, and the buckets of the runner are always filled with the water which drives them forward. Working in this way by water pressure due to the weight of the water column, it is not necessary that the turbine should be placed at the extreme bottom of the fall, provided an air-tight casing is continued below the runner so as to take advantage of the solid water

column below the turbine. Such an arrangement is called a draft tube, and may be of any length up to the full column which may be supported by atmospheric pressure, provided the body of water shall be continuous so that there shall be no loss of head due to the drop of the water from the wheel to the level of the water in the tail race. It is as if the column below were pulling and the column above pushing, the runner being in a solid stream extending from the highest to the lowest level of water used. As a matter of practice the draft tube is generally made considerably shorter than the column of water which might be supported by atmospheric pressure, generally less than 20 feet, depending somewhat on the size of the wheel. With longer tubes it is difficult to preserve a continuous column, which is necessary in order to utilize the full power of the water.

Nearly all American turbines are of this so-called "pressure" type. There is, however, another type of turbine wheel used somewhat extensively abroad, and occasionally manufactured in this country, which without any very great change in character of the structure operates on an entirely different principle. There are present, as before, guide blades delivering the water from buckets to the runner, but the spaces between these blades are so shaped and contracted as to deliver the water to the runner as a powerful jet. The energy of water pressure is converted into the kinetic energy of the spouting jet, and the buckets of the runner are not filled solidly and smoothly with the water, but serve to absorb the kinetic energy of the jets, and discharge the water below at a very low velocity. Such turbines are known as impulse turbines, from the character of their action. In the pressure turbines the full water pressure acts in the runner and in the space between the guides and the runner. In the pressure turbine each space between the guide blades acts so as to form a water jet, which impinges fairly on the bucket of the runner without causing a uniform pressure either thoroughout the bucket spaces or in the space between runner and guides. It is not intended that the passages of the wheel should be, as in the pressure turbine, entirely filled with the water, nor is it best that they should be. Fig. 159 gives a sectional view from Unwin showing the arrangement of the guide blades and buckets of an impulse

turbine, in which the flow is, as in the pressure turbine previously shown, in general along the axis of the wheel. An impulse turbine necessarily loses all the head below the wheel and cannot be used with a draft tube.

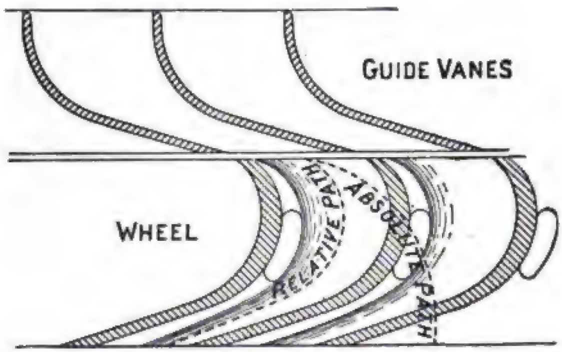


FIG. 159.

Occasionally an attempt is made in the so-called limit turbines so to design the guides and buckets that the jets may completely fill the buckets, which are adapted exactly to the

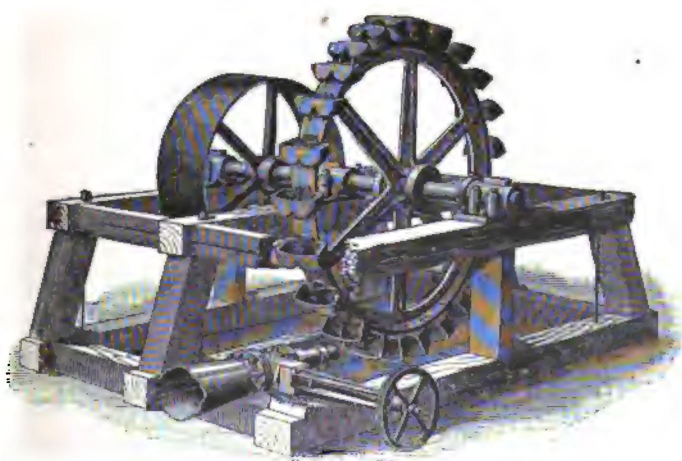
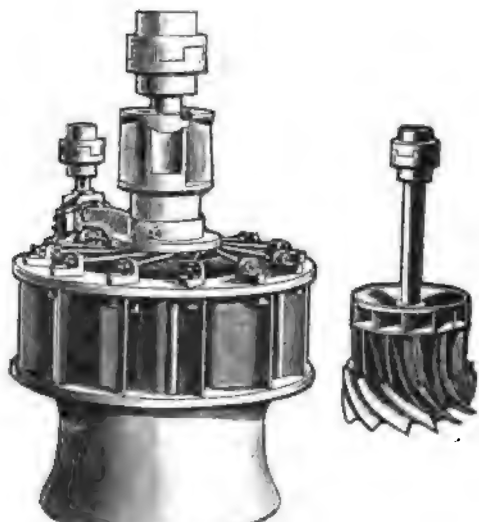


FIG. 160.

shape of the issuing stream. In such case the turbine works as an impulse wheel or as a pressure wheel, according as the draft tube is not or is used.

A modified impulse turbine, largely used for very high heads of water, is found in the Pelton and similar wheels, in which the impulse principle is used through a single nozzle acting in succession on the buckets of a wheel which revolves in the same plane with the issuing jet. Such a Pelton wheel is shown in Fig. 160. Occasionally two or more nozzles are used, delivering water to the same wheel. Impulse wheels of this class are exceedingly simple and efficient, and work admirably on high heads of water. They are morever very flexible in the matter of obtaining efficiently various speeds of rotation from the same head of water, as the whole structure is so simple



FIGS. 161 AND 162.

and cheap that it can be modified easily to suit varying conditions.

It is obvious that the operation of such an impulse wheel is similar to that of a true impulse turbine, in which only one, or at the most three or four jets from the guide blades are utilized. Most of the hydraulic work done in this country is accomplished with pressure turbines, which are worthy, therefore, of some further description. A small but important portion is accomplished by Pelton and other impulse wheels, and

in a very few instances the impulse turbine proper has been used.

There are manufactured in this country more than a score of varieties of pressure turbines. They differ widely in design and general arrangement, but speaking broadly it is safe to say that most of them are of the mixed discharge type, in which the water passes away from the buckets of the runner

FIG. 163.

in more than one direction with reference to the axis of the wheel. It would be impossible to describe even a considerable part of them without making a long and useless catalogue. The essential points of difference are generally in the construction of the runner and in the mechanism of the guide blades. In a good many turbines regulation is accomplished by shifting the guide blades so as to deliver more or less water to the runner. A few types will serve to illustrate the general character of some of the best-known American wheels. Fig. 161 shows the so-called Samson turbine of James Leffel & Co., and Fig. 162, the runner belonging to it. This wheel is of

the class which regulates by shifting the guide blades, which are balanced and connected to the governor by the rods at the top of the casing shown. The water enters the guide blades inwardly, and the runner is provided as shown with two sets of buckets; the upper set discharging inwardly, the lower and larger set downwardly. The action of the wheel is almost equivalent to two wheels on the same shaft, the intention being to secure an unusually large power and speed from a given

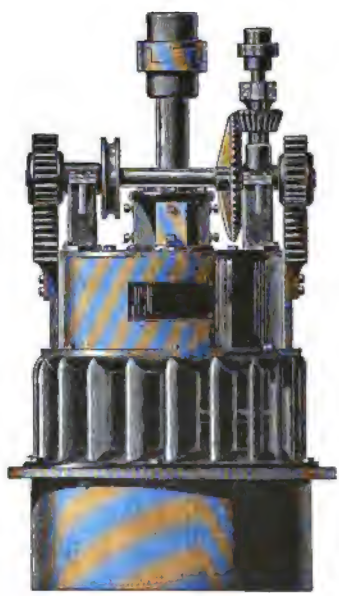


FIG. 164.

head of water on a single wheel structure. This result is, as might be anticipated, accomplished, and for a given diameter the Samson turbine has a speed and power considerably greater for a given head than found in the usual standard single wheels. As before remarked, however, it is almost, mechanically speaking, equivalent to two wheels through its peculiar feature of double discharge through independent buckets.

Another very excellent and well-known wheel is the Victor

turbine, shown in Fig. 163. In this wheel the gate is of the so-called cylinder type, which lengthens or shortens the apertures admitting water to the guide blades. The runner of this wheel is so shaped that the water is discharged inwardly and downwardly. The area of the runner blades exposed to the full water pressure is notably great. The cylinder

FIG. 165.

form of gate is rather a favorite with American wheel manufacturers, and is intended to secure a somewhat uniform efficiency of the wheel, both at full and part load, although how completely it does this is a matter which, of course, is still in dispute. The wheel shown, however, is an exceptionally good and efficient one, so far as can be judged from general practice. The same makers also manufacture a wheel with shifting guide blades.

Another excellent wheel of the cylinder gate type, the

McCormick, is shown in Fig. 164. The runner of this wheel has its main discharge downward. It has a rather large power for its diameter, owing to the proportion of the runners, and is well known as a successful and typical downward discharge wheel.

Another familiar wheel is the so-called New American (Fig. 165). Like the Samson wheel, first described, the regulation is by shifting the position of the guide blades, which are comparatively few in number and deliver the water inwardly to a runner, Fig. 166, which discharges inwardly and downwardly without,

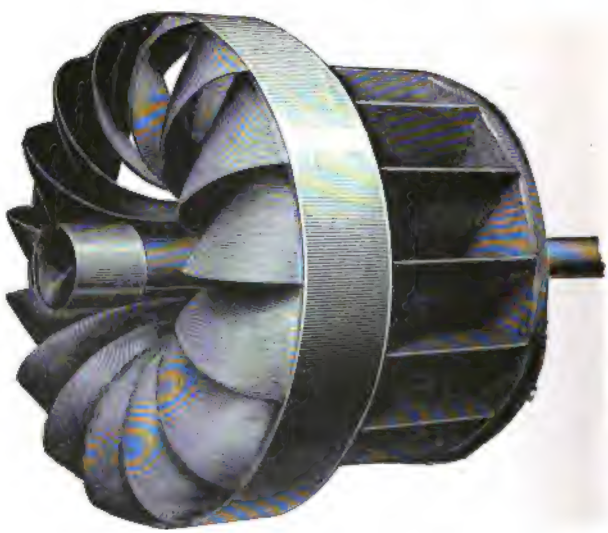


FIG. 166.

however, having the duplex character peculiar to the Samson wheel. These four turbines are typical of the construction and arrangement used by first-class American manufacturers. They are all arranged for either horizontal or vertical axes, and for purposes of driving electrical machinery are generally used in the horizontal form. All of them, particularly the two first mentioned, have been widely used for electrical purposes. They are all practically pure pressure turbines and are installed usually with draft tubes of appropriate length. They are often, too, installed in pairs, two wheels being placed on the same shaft, fed from a common pipe but discharging through

separate draft tubes. The arrangement of these draft tubes is very various, as they can be placed in any position convenient for the particular work in hand. Fig. 167 shows a common arrangement where a single wheel is to be driven. The water enters through the penstóck, passing into the wheel case through the wheel, which has, as is generally the case except with very low heads, a horizontal axis, and thence passes into

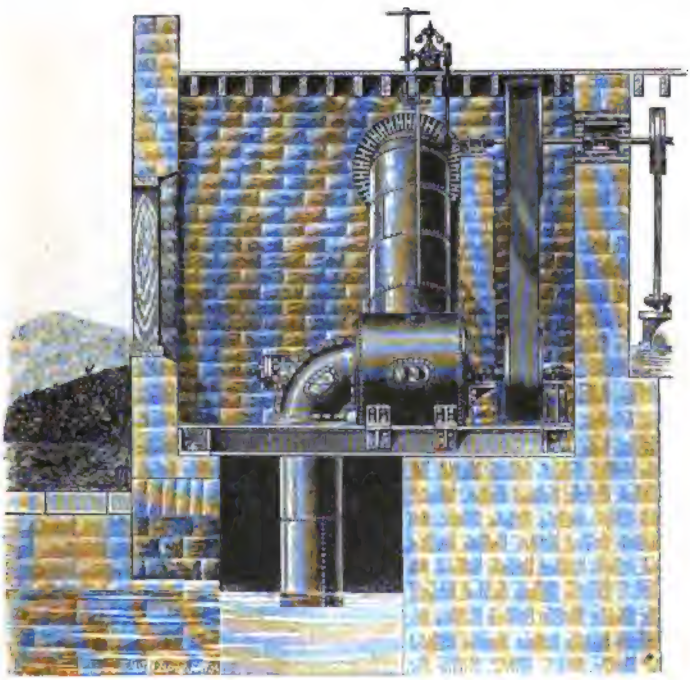


FIG. 167.

the tail race through the draft tube, shown in the lower part of the cut. The full head in the particular case shown is 43 feet, so that the draft tube is fairly long. Where double wheels are employed, there is no longer any necessity of taking up the longitudinal thrust of the wheel shaft, and an arrangement frequently followed is shown in Fig. 168, which gives a very good idea of the general arrangement of the pair of horizontal turbines, which may be directly coupled to the load or, as in the case just mentioned, drive it through the medium of belts.

Wherever possible, it is highly desirable to employ these horizontal wheels for electrical purposes, inasmuch as power has, in most cases, to be transferred to a horizontal axis, and the use of a vertical shaft wheel necessitates some complication and loss of power in changing the direction of the motion. Occasionally a vertical shaft wheel is used for electrical purposes,

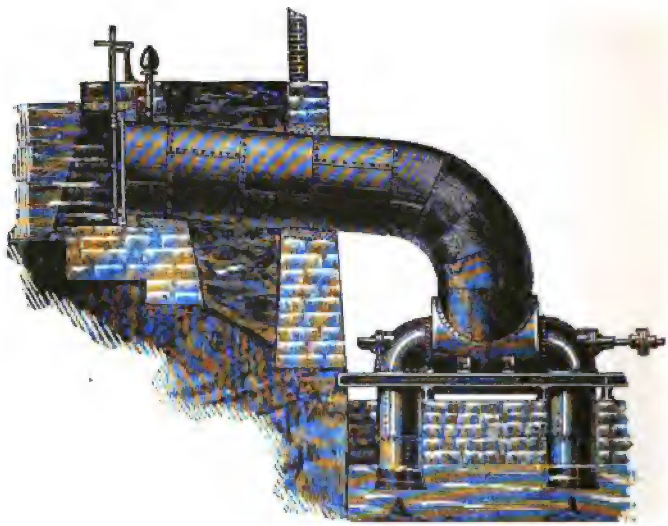


FIG. 168.

driving a dynamo having a vertical armature shaft. This practice is not generally to be recommended, as it involves special dynamos, and a somewhat troublesome mechanical problem in supporting the weight of the armature, which is generally carried by hydraulic pressure. A fine example of this arrangement is to be found in the great Niagara Falls plant.

The use of pressure turbines for driving electrical machinery is exceedingly convenient on low or moderate heads, say up to 50 or 75 feet. With higher heads than this the rotative speed becomes inconveniently great; for example, under 100 feet head, 150 HP can be obtained from a wheel a little more than 15 inches in diameter, at a speed of more than 1,000 revolutions per minute. At 200 feet head, the power for the same wheel will have risen to about 400 HP and the speed to nearly 1,300. This is a rather inconvenient speed for so large a power,

and it is necessitated by the fact that a pressure turbine to work under its best conditions as to efficiency, must run at a peripheral speed of very nearly three-quarters the full velocity of water due to the head in question. If, therefore, turbines are used for high heads, either the dynamos to which they are coupled must be of decidedly abnormal design, or the dynamo must be run at less speed than the wheels.

The former horn of the dilemma was taken in the Niagara plant, and involved some very embarrassing mechanical ques-

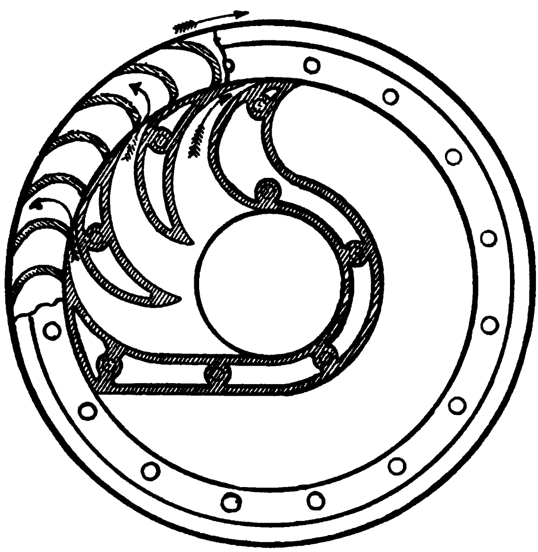


FIG. 169.

tions in the construction of the dynamos. Where belts are permissible the other practice is the more usual, of which a good example is found in the large lighting plant at Spokane Falls, Wash., where the wheels are belted to the dynamos for a reduction in speed instead of an increase, as is usually the case.

Impulse wheels are regularly made at present by only one American company, the Girard Water Wheel Co. of San Francisco, Cal. The wheel manufactured by them is one with a well-known foreign reputation. Its general arrangement is well shown by the diagram, Fig. 169. The Girard impulse turbine is

of the outward flow type, a form rather rare in pressure turbines. The water enters the wheel centrally through a set of guide blades, which form a series of nozzles from which the water issues with its full spouting velocity and impinges on the buckets of the runner, which surrounds the guide blades. The discharge is virtually radially outward. Regulation is secured by a governor which either cuts off one or more of the nozzles or may be arranged by swinging guide blades to contract all or a part of the nozzles. In either case, there is no water wasted, and the wheel works efficiently at practically all loads.

Like others of its type, the peripheral speed of the wheel when worked under its best conditions for efficiency is very nearly one-half the spouting velocity of the water as it issues from the nozzle. This produces for a wheel of given diameter a lower speed for the same head than in the case of pressure turbines, while the use of a large number of nozzles working simultaneously on the runner gives a higher power for the same diameter than in the case of the Pelton or similar wheels, which use a few nozzles with jets applied tangentially; hence such impulse turbines occupy an exceedingly useful place in the matter of speed, aside from all questions of efficiency.

Under moderately high heads, from 100 up to 300 or 400 feet, they give a much greater power for a given rotative speed than impulse wheels employing only two or three nozzles. On the other hand they do not run inconveniently fast, as is the case with pressure turbines under such heads. At extremely high heads they give, unless operated with only one or a few nozzles, so great power as to be inconvenient for the high speed attained, so far at least as the operation of dynamos is concerned. At very low heads there is material loss from the fact that the wheel cannot be used with the draft tube, and consequently a certain amount of the head must be sacrificed to secure free space from the wheel to the tail water. These Girard turbines are made with both vertical and horizontal axes, and are applicable to electrical work with the same general facility which applies to other types of wheel. Their strong point is economical and efficient regulation of the water supply, together with high efficiency at moderate loads.

The Pelton wheel, already shown in Fig. 160, may be regarded as an impulse turbine having a single nozzle, and that applied tangentially. These wheels have proved immensely effective for heads from several hundred up to a couple of thousand feet. Like the true impulse turbines, the peripheral speed should be half the spouting velocity of the water, hence by varying the dimensions of the wheel a wide range of speed can be obtained, which is exceedingly convenient in power transmission work, permitting direct coupling of the dynamos under all sorts of conditions. They are not infrequently made with two or three nozzles, which give, of course, correspondingly greater power for the same speed. At heads of only 100 or 200 feet these wheels with their few nozzles give an inconveniently low rotative speed for the power developed, and are at their best in this respect between 300 and 1,000 feet. The Pelton wheel is usually regulated by deflecting the nozzles away from the buckets of the wheel, a very effective but most inefficient method, so far as economy of water is concerned. The wheel has, however, a very high normal efficiency, certainly as high as can be reached with any other form of hydraulic prime mover. The practical results given by this class of wheel, both of Pelton and other makes, are admirable under conditions favorable to their use.

Another wheel of this class is the Leffel "Cascade" water wheel. Two complete rings of buckets are employed for this wheel, instead of the divided buckets of the Pelton form, and the wheels are arranged to be supplied from several nozzles, of which one or more are put into use according to the necessities of regulation. The Cascade wheel therefore occupies a place, as it were, between the Pelton wheel and the impulse turbine, resembling the former in the arrangement of its multiple jets, and the latter in the method of regulation by cutting off completely some of the nozzles.

From the foregoing it will be appreciated that each of the three general classes of wheels described, pressure turbines, impulse turbines and tangential impulse wheels, has a sphere of usefulness in which it can hardly be approached by either of the others. It is worth while, therefore, to examine somewhat in detail the conditions of economy under various circumstances.

The pressure turbine has its best field under relatively low and uniform heads. By means of the draft tube no head is lost, as is the case with that portion of the head which lies between the turbine and the tail water in the use of impulse wheels of any description. Further, the pressure turbine under all heads gives a higher relative speed than the impulse wheels, whether of the tangential or turbine variety, and under low heads is apt to be of less bulk and cost and to give a more convenient speed for electric work; hence these pressure turbines have been more extensively used than any other variety of water wheels in the enormous hydraulic developments of the last quarter of a century. Furthermore, the pressure turbine has, under favorable conditions, as high efficiency as any known variety of water wheel. The losses of energy are mainly of four kinds:

1. Friction of bearings, usually small.
2. Friction and eddying in the wheel and guide passages.
3. Leakage, and
4. Unutilized energy of other kinds, largely owing to imperfect shaping of the working parts, or loss of head.

With the best construction these losses aggregate 15 to 20 per cent. Of them the shaft friction is the smallest and the loss from friction and eddies in the wheel the largest, probably fully half of the total loss, particularly under high heads. This efficiency is approximately true of the better class of turbines, whether of the pressure or impulse variety. Under low and uniform heads the pressure turbine probably is capable of a little better work than the impulse variety, but both suffer if the head varies. The curves, Fig. 170, show efficiency tests on four first-class pressure turbines made with the greatest care at the Holyoke testing flume, probably the best equipped place in the world for making such tests. It should be noted that the efficiency of all the wheels shown is good; over 80 per cent. at full admission of water; at partial admission the efficiencies vary more between the individual wheels. This variation is largely due to the methods of regulating the flow employed. These are in general three:

1. Varying the number of guide passages in use.
2. Varying the area of these guide passages by moving the guide blades.

3. Varying the admission to the guide passages by a gate covering the entrance to all of them.

The first method is particularly bad, as the buckets are at one moment exposed to full water pressure and then come opposite a closed passage, setting up a good deal of unnecessary shock and eddying. It is a method that is scarcely ever used in this country. Between the other two it is not so easy to choose. Both have strong advocates among wheel makers; some com-

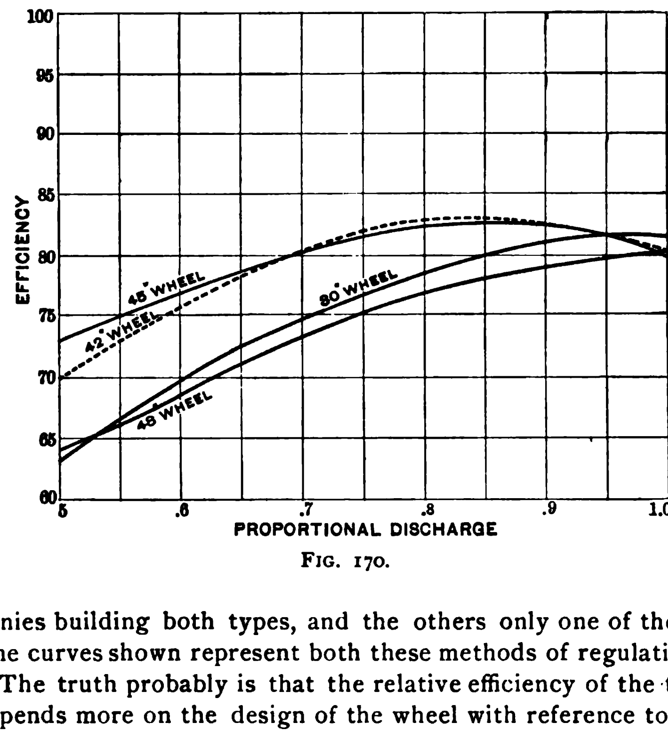


FIG. 170.

panies building both types, and the others only one of them. The curves shown represent both these methods of regulation.

The truth probably is that the relative efficiency of the two depends more on the design of the wheel with reference to its particular form of regulation, than on the intrinsic advantages of either form. Turbines are generally constructed so that the point of maximum efficiency is rather below the maximum output, as a little lee-way is desired for purposes of regulation under varying heads, so that the design is arranged to give the best efficiency of which the wheel is capable at a point a little below full admission. These efficiency curves were taken at heads of from 15 to 18 feet and show what can be regu-

larly accomplished by good wheel design. They are neither phenomenally high nor unusually low. Occasionally efficiencies are recorded slightly better than those shown. In this connection it is desirable to state in the way of warning, that there was obtained at the Holyoke flume some years ago a series of tests of turbines of more than one make, which showed enormously high efficiency, afterward traced to a constant error in the experiments. As the fact of the error was not so generally known as the result of the tests, occasionally reports are heard of phenomenal turbine efficiencies which are given in entire good faith, but based on errors of observation. It is only fair to say that the tests now made at the Holyoke flume are worthy of entire confidence.

As regards impulse turbines, data are hard to obtain. Those which are available indicate, however, that with an efficiency probably a little less at full load than that of pressure turbines under moderate heads, the half load efficiency is generally considerably higher. This is owing to the fact that the buckets of the runner work entirely independently of each other, and the water acts in precisely the same way on each bucket whether it is received from all the nozzles, formed by the guide blades, or from a part of them. The impulse turbines are generally regulated by cutting off more or less of the nozzles. The shaping of the surfaces in the runner and guide blades, and the smoothness of the finish, are of more importance in these wheels than in the ordinary pressure turbines. The impulse turbines are, as has already been stated, peculiarly adapted in point of speed and general characteristics for use on moderately high heads, and in this work they give a better average efficiency and more economical use of water than any of the pressure turbines. For low heads their advantages are far less marked, and the pressure turbines are generally preferred.

The tangential impulse wheels are, at full admission of water, of an efficiency fully equal to that of the best turbines. At partial admission they cannot be expected to give the same results as do the best impulse turbines, inasmuch as they regulate either by deflecting the nozzle away from the buckets, and hence wasting water, or by more or less throttling of one or more of the individual nozzles; hence using the water less

effectively. In this latter method of regulation, there are disadvantages arising from the small number of nozzles, whereby it is impracticable to obtain a close regulation of speed by simply cutting off nozzles as in the impulse turbines. For very high heads, however, the tangential wheels are preferable to any turbines, as they give a better relation between power and speed, so far as driving electrical machinery is concerned, and their extreme simplicity is favorable to good continuous working under the enormous strains produced by the impact of water at great spouting velocities.

To summarize, pressure turbines are admirable for low and uniform heads, particularly where the load is steady. The impulse turbines give more efficient use of water at part load, and a more convenient speed on moderately high heads. The tangential impulse wheels do relatively the best work under very high heads, and where water does not have to be rigidly economized. Each of the three classes has decided advantages over the others in particular situations, and the full load efficiency of all three is approximately equal. The choice of either one of these types should be made in each individual case in accordance with the hydraulic conditions which are to be met. The choice between particular forms of each type is largely a commercial matter, in which price, guarantees, facility of getting at the makers in case of repairs, standard sizes fitting the particular case in hand and similar considerations are likely to determine the particular make employed, rather than any broad difference in construction or operation.

The success of a power transmission plant depends quite as much on careful hydraulic work as on proper electrical installation. The two should go hand in hand, and any attempt, such as is often made, to contract for the two parts of the plant independently of each other, or to engineer them independently, generally results in a combination of electrical and hydraulic machinery that is far from being the best possible under the conditions, and is quite likely to be anything but satisfactory.

The hydraulic and electrical engineers should go over the arrangement of the plant together with a view to adapting each class of machinery to the other as perfectly as possible, in order to get a symmetrical whole. Many troublesome

questions have to be encountered, and only the closest study will lead to perfectly successful results. One of the commonest and most serious difficulties met with in laying out an electrical and hydraulic plant for transmission work, lies in the variability of the head of water. There are comparatively few streams from which can be obtained an invariable head practically independent of low water or freshets. The usual condition of things is to find a fairly uniform head for nine or ten months in the year, and rather wide variations during the remainder of the time. It is not at all uncommon to meet a water power which even when very skillfully developed, will still entail upon the user a variation of 25 or 30 per cent. available head.

At the time of high water this appears as a rise of water level in the tail race, so as to diminish the head available for the wheels. In times of low water, the head might be normal, but the quantity of water altogether insufficient. Any variations of this kind are of a very serious character, because they not only vary the amount of power which is available, but they change the speed of the wheels so that the dynamos no longer will operate at their proper speed and hence will change in voltage, and if alternating apparatus is used, in frequency also, which is even more serious. For example: Under 24 feet head one of the well-known standard wheels gives nearly 650 HP at 100 revolutions per minute. Under 16 feet head the same wheel would give only 352 HP at 82 revolutions.

The lack of power occurring at the time of high water is serious. The change of speed, although not great, is very annoying, and should be avoided if possible. Changes much greater than this are common enough. The season of reduced head is generally short, not over a couple of months, often only a week or two, and this renders the situation doubly embarrassing, because during a large part of the year the same wheel must be able to operate economically. The methods taken to get out of this difficulty of varying head are various; most of them bad. One of the commonest is to arrange the wheels to operate normally at partial gate, then on the low heads to throw the gate wide open and obtain increased power. On the high heads the wheel is throttled still more. Such an arrangement works the dynamo in a

fairly efficient fashion, but the wheel, as a rule, quite inefficiently a large portion of the time, as may be seen by reference to the efficiency curves of the wheels just given. It is a practice similar to that which one would find in working an engine at part load. For moderate variations of head not exceeding 10 per cent., the loss of efficiency is not so serious as to bar this very simple plan, but under conditions too frequently encountered, these variations of efficiency would be so great as to make the method exceedingly undesirable.

Hydraulic plants are occasionally operated without any reference to economy of water, and in such cases the practice of operating normally at part gate is frequently followed, but it must be remembered that as water powers are more and more developed, economy of water becomes more and more necessary, and in every case should be borne in mind even if it is not rendered necessary by conditions actually existing.

Another method of overcoming the difficulties due to variations of head is the installation of two wheels on the same shaft, one intended to give normal power and speed at the ordinary head, the other at the emergency head. This practice is carried out in various forms. Sometimes two wheels may be mounted on the same horizontal or vertical axis, and one of them is disconnected or permitted to run idle except when actually needed. Another modification of the same general idea is the use of a duplex wheel with the runner and guides arranged in two or three concentric sets of buckets, which can be used singly or together according to the head which is available.

A fine example of this practice is found in the great power plant at Geneva, to which reference has already been made, where the head varies from 5½ to 12 feet. Here the turbines have buckets arranged in three concentric rings, the outermost being used at the highest head and all three at the lowest head. Under the latter condition, the average radius at which the water acts upon the wheel is diminished at the lower heads and the speed is therefore increased. The various combinations possible with the rings or buckets are so effective in keeping the speed uniform that the extreme variation of speed under

the maximum variation of head is only about 10 per cent. Such a triplex turbine is of high first cost, but is decidedly economical of water at normal load. Still another variation of the double turbine idea consists of installing two turbines for each unit of power, one acting directly, the second through the medium of belts. The direct-acting turbine is intended for normal load, the belted turbine of larger dimensions for use during the periods of low head.

This arrangement is used in the large power transmission plant at Oregon City, Ore. It is economical of water, but is mechanically somewhat complicated. It is probably on the whole less desirable than the installation of two turbines on the same shaft, or the duplex or triplex arrangement just referred to. Where two turbines are operated on the same shaft, it is always possible to arrange the turbine designed to operate on the lower head so as to run at a disproportionately high velocity with some loss of efficiency, and so to hold the speed fairly uniform.

Still another method of counteracting the variation of head is applicable only where the power is transmitted from the turbine by gears or belts. In this case it is always possible to operate the machinery under the reduced head with some loss of output, but still at or near the proper speed. Whatever way out of the difficulty is chosen, it should be borne in mind that the most desirable, on the whole, is the one which will work the wheels during the generally long period of fairly steady head at their best efficiency. If there is to be any sacrifice of efficiency, it should by all means be for as short a time as possible, and therefore should be at the periods of extreme low head. At such times water is generally plenty, while at the higher heads economy in its use is more necessary.

REGULATION OF WATER WHEELS.

For many years there have been bad water wheel governors and worse water wheel governors, but only recently have there appeared governors which may be classified as good from the standpoint of the electrical engineer. It has been necessary to go through the same tedious waiting and experiments that

were encountered before dynamo builders could find engines which would hold their speed at varying loads. Until the advent of electrical transmission work, water wheels were most generally employed for certain classes of manufacturing, such as textile mills, where the speed must be quite uniform, but where at the same time the load is almost uniform; or on the other hand for saw mills and the like, where constant speed is of no particular importance.

The action of water wheel governors as regards the way in which they vary the supply of water is very different; some merely act to open or close the head gates; others to work a cylinder gate immediately around the wheel, and still others to vary the area of the guide passages, as in the so-called register gate turbines.

In whatever way the governing action takes place, its result is too often unsatisfactory, due to the great difficulty that has to be encountered, the immense inertia of the water and of the moving parts of the wheel. Both water and wheel are sluggish in their action, and as a result some time elapses after the governor has produced a change of gate before that change becomes effective. Meanwhile the speed has fallen or risen to a very considerable extent, and perhaps in addition the load has again changed so that by the time the speed of the wheel has been sensibly affected by the governor, the direction of the governing action may be exactly opposite to that which at the moment is desirable. Even if this is not the case the governing is usually carried too far, being continued up to the time at which the wheel is affected and reacts on the governing apparatus, hence another motion of the governor becomes necessary to counteract the excess of diligence on the part of the first action. In other words, the governor "hunts," causing a slow oscillation of the speed about the desired point, an oscillation of decreasing amplitude if the new load on the wheel be steady.

This sluggishness of reaction to changes indicated by the governor is the most formidable obstacle to the proper control of the water wheels. To overcome it, even in part, it is necessary that the movement of the gates be comparatively active, if the changes of load are frequent, and this entails still further difficulty by causing severe strains on the mechanism

and the gates, particularly if the water is led to the turbine through a long penstock. In the latter case the variations in pressure produced by rapid governing are often dangerous, and have to be counteracted by air chambers, stand pipes or the like, and aside from all this there is a still further difficulty in the considerable weight of the gates and the pressure against which they have to be operated, so that the amount of mechanical power controlled by the governor must be very considerable.

A very large variety of governors have been designed to meet the very serious difficulties just set forth. Most of them have been abject failures, and those that may be really accounted of some considerable value for electrical work may be counted on the fingers of one hand.

Water wheel governors may be divided into three general classes: First we have a large range of contrivances, mostly antiquated, which attempt to control the position of the gates of a wheel more or less directly by means of a centrifugal governor of some sort. Next come indirect-acting centrifugal governors. These are arranged with various sorts of gearing, operated from the water wheel shaft and controlled in one way or another by a governor. Finally comes the relay class of governors, wherein all the work possible is taken off the centifugal governor, and its function is reduced to throwing into action a mechanism for moving the gates which may be quite independent of any power transmitted from the wheel to the governing mechanism. The various classes of hydraulic, pneumatic and electric governors are worked in this way. Their general characteristic is that their sole function in governing is to work the devices which control the secondary mechanism, which consists, in various cases, of hydraulic cylinders operating the gates, pneumatic cylinders serving the same purpose, or electric motors which open or close the gates by power derived from the machines operated by the turbines.

A vast amount of ingenuity has been spent in trying to work out regulators of the first and second mentioned forms. Almost every possible variety of mechanism has been employed to enable the governor to apply the necessary power to the mechanism operating the gates. The general form of most of

these governors is as follows: Power is taken from the wheel shaft by a belt to the governor mechanism, where it serves at once to drive the governor balls, and to work the gates when the governor connects the gate-controlling gears to the pulley which supplies the power. This is generally done by friction cones or their equivalent, thrown into action in one direction when the governor balls rise and in the other direction when they fall.

Sometimes this mechanism is varied by employing a pair of oscillating dogs, one or the other of which is thrown into appropriate gearing by the governors. There are many governors of this kind on the market, and where the load is fairly steady and no particular accuracy of regulation is necessary, they have given good satisfaction. The fault with all governors of this sort is that the centrifugal balls either lack sensitiveness or lack power. If the governor works at all rapidly in moving the gates, too heavy a load is thrown on the governor for any but a massive mechanism; or, on the other hand, if the gates are worked slowly, the governor in itself lacks sensitiveness.

In most cases the gates are made to move quite slowly. In the attempt to get sensitiveness, the friction wheels or dogs are often adjusted so closely that the governor is in a constant slight oscillatory motion, but when its action is really needed, as in the case of a sudden change of load, response generally does not come quickly enough. It is of course possible to construct a mechanical relay which would possess both power and sensitiveness, but nearly all the hydraulic governors made on this principle lack one or the other, and sometimes both.

The third type of governor, as mentioned, is not open to the objections noted, if properly designed, inasmuch as it is a comparatively easy matter to make a balanced hydraulic or pneumatic valve which can be worked even by the most sensitive of governors, and yet can apply power enough to move heavy gates as rapidly as is consistent with safety. In addition, such governors can be made to work with a rapidity depending on the amount of change in speed, so that if a heavy load is thrown on the wheel, the relay valve would be thrown wide open and consequently bring a great and

immediate pressure to bear upon the gates. In the so-called electric governors, the function of the governor balls is merely to make in one direction or the other the electrical connections to a reversible motor which handles the gates. This relay class of governors has been recently worked out with considerable care, and is capable of giving surprisingly close regulation even under widely varying loads, results comparable even with those obtained from a steam engine governor.

A fourth type of water wheel governor is independent of any centrifugal device and operates by a differential speed mechanism, so that wherever the speed of the wheel varies from a certain fixed speed maintained by an independent motor, the gates are opened or closed as occasion demands. The difficulty here is to get a constant speed which will not be sensibly altered when the load of working the gates is thrown on the governor mechanism. Some species of relay device is almost necessary to the successful operation of a differential governor, but with such an adjunct very close regulation can be and is obtained.

Up to the past few years almost all hydraulic governing has been by mechanisms of the first class, and it is only recently that the relay idea has been worked out carefully, both for centrifugal and differential mechanisms, so as to obtain anything like satisfactory results for electrical work where close regulation of speed over a wide variation of load is very necessary.

For electrical purposes, several rather interesting governing mechanisms have been tried, which do not fall into any of these classes, inasmuch as their function is to keep the load constant and prevent variations of speed instead of checking these variations after they have been set up. Such governors (load governors they may properly be called) operate by electric means, throwing into circuit a heavy rheostat or a storage battery when the electrical load falls off, and cutting these devices out again when the load in the main circuit increases. These governors have in several instances been applied with success to controlling the variable loads found in electric railway stations operated by water wheels. But they waste energy in a very objectionable manner, and at best can only

be regarded as bad makeshifts, out of the question when there must be any regard for economy of water, and only to be tolerated in the lack of an efficient speed regulator.

Occasionally electric governors operated by the variations in the voltage of the circuit supplied have been tried, but these are open to two serious objections: In the first place they do not hold the voltage steady for the same reasons that most speed regulators do not hold the speed steady. Secondly, they regulate the wrong thing. In transmission plants, most of which are and will be operated by alternating currents, it is important that the cycles be kept uniform. If the voltage

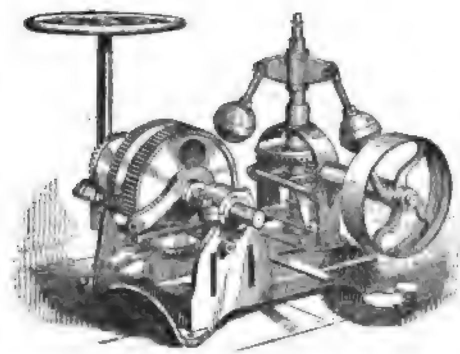


FIG. 171.

is kept constant by varying the speed, the cycles will be subject to enough variation to be very annoying in the operation of motors.

To pass from the general to the special. Fig. 171 shows a typical water wheel governor of the first class, that is, of the kind operated directly by the wheel through a system of dogs worked by a fly ball governor. There is here no attempt at delicate relay work, and the resulting mechanism, while quite good enough for rough-and-ready work, is of little use for any case where a variable load must be held to its speed with even a fair degree of accuracy. The cut shows the construction well enough to render further description superfluous. Governors like these were practically the best available for many years, and proved to be cheap and durable, but they seldom governed much more than to keep the wheels

from racing dangerously when the load was thrown off, or slowing down permanently when the load came on. It is not too much to say that they never should be used in connection with an electrical station, unless combined with intelligent hand regulation—which at a pinch is not to be despised.

Of the indirect acting and relay governors there are many species, most of which had better be consigned to the oblivion of the scrap heap. But out of the manifold inventions and experiments good has come, so that at the present time there are two or three delicate relay governors capable of holding the wheel speed constant within a very narrow margin indeed. Others of similar excellence will probably be evolved, but just now these three, the Lombard, Replogle and the Faesch-Piccard, form a class by themselves, to judge from the results obtained. The first named has given very remarkable results in several transmission plants in which it has been employed—results quite comparable with those obtained from a well-governed steam engine. The second has given excellent results in the Oregon City transmission and elsewhere, while the last has been adopted for the great transmission at Niagara Falls and has done its work well. All three are somewhat complicated and expensive, but they actually do govern with considerable precision.

The Lombard governor, Fig. 172, is an hydraulic relay in principle. The gate-actuating mechanism is a rack gearing into a pinion, and driven to and fro by the piston of a pressure cylinder. The working fluid is thin oil, kept under a pressure of about 200 lbs. per square inch. This pressure is supplied by a pump driven by the pulley shown in the figure and operating to keep up a 200 lb. air pressure in the pressure chamber at the base of the governor, above the oil that partially fills it. This chamber is divided into two sections, the one holding the oil under pressure, the other being a vacuum space kept at reduced pressure by the pump system.

The circulation of oil is from the pressure chamber through the piping system and valves to the working cylinder, and thence into the vacuum chamber, whence it is pumped back into the pressure chamber again. The governor proper consists of a sensitive pair of fly balls operating a balanced piston valve in the path of the pressure oil. A motion of $\frac{1}{64}$ of an inch at

the valve is sufficient to put the piston into full action and open or close the gates. Sensitive as this mechanism is, it would not govern properly without the addition of an ingenious device, peculiar to this governor, to take account of the inertia of the system. The weakest point of all such governing mechanisms has been their helplessness in the matter of inertia. If a sensitive governor of the first class be set to regulate a

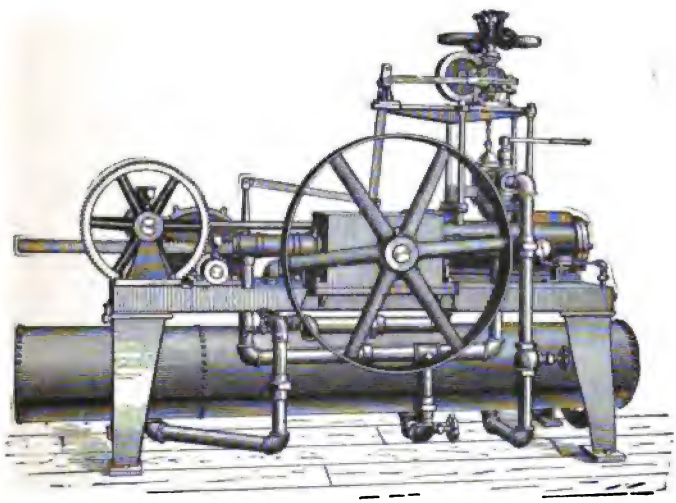


FIG. 172.

wheel, we encounter the following unpleasant dilemma: If the mechanism moves the gates quite slowly, it will not be able to follow the changes of load. If it moves them rapidly the governing overruns on account of the inertia of the whole wheel system, so that the apparatus "hunts," perhaps the worst vice a governor can have when dynamos are to be governed. Hence most governors have either been unable to follow a quickly varying load at all, or they have made matters worse by hunting.

In the Lombard governor special means are provided to obviate hunting. The bell-crank lever seen in the background of Fig. 172 is actuated by the same movement that works the wheel gates, and moves the governor valve independently of

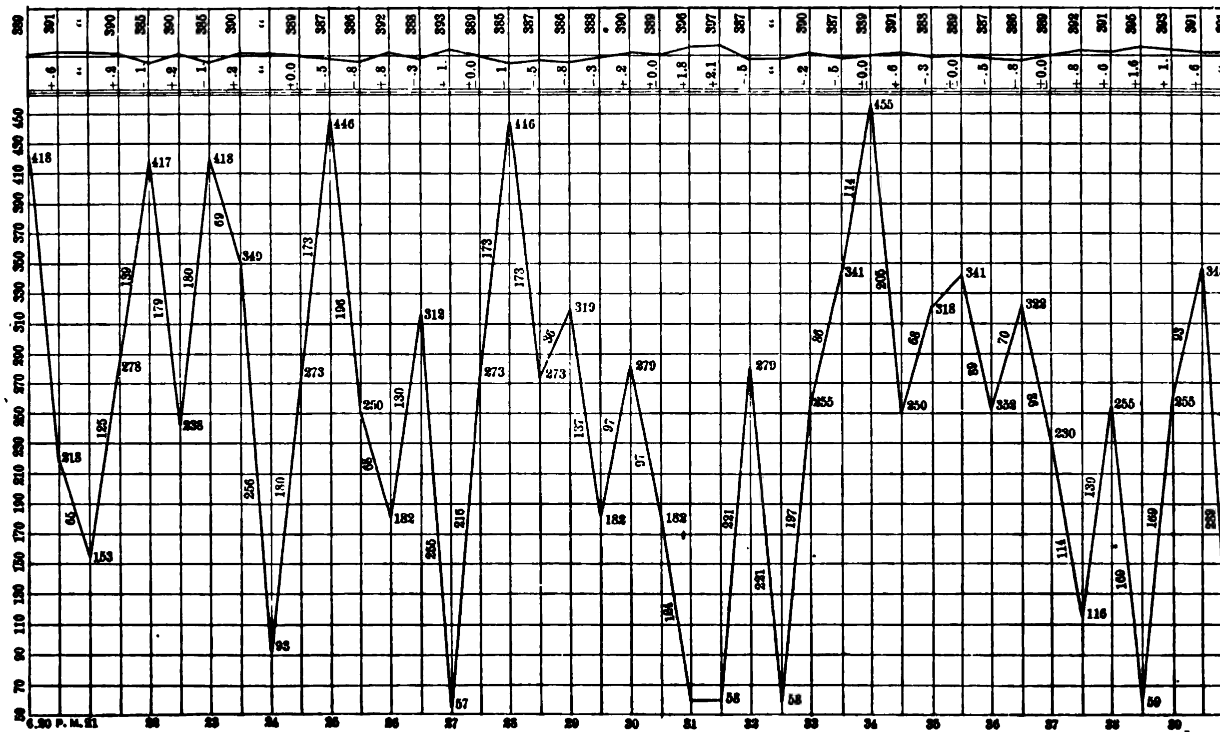


Fig. 173.

the fly balls. Its office is to promptly close the valve far enough ahead of the termination of the regular gate movement to compensate for inertia. For example, if the speed falls and the fly balls operate to open the gate wider, the lever in question closes the governor valve before the fly balls are quite back to speed, so that instead of overrunning and hunting, the governing is practically dead beat.

The result obtained with this governor well seen in Fig. 173. This diagram is taken from a plant operating an electric street railway—perhaps the worst possible load in point of irregularity. The diagram shows a maximum variation of 2.1 per cent. from normal speed, lasting less than one minute, under extreme variation of load. These results are entirely authentic, the readings having been taken jointly by the representatives of the governor company and the local company. Speed was taken by direct reading tachometer and load from the station instruments.

The Faesch & Piccard governor has taken several forms, the idea of a sensitive relay mechanism being carried through all of them. An hydraulic relay has been successfully employed abroad. Here the function of the fly balls is reduced to moving a balanced valve controlling hydraulic power derived from the natural head, or from a pressure cylinder. There is no mechanical provision against hunting, but the speed of governing is adjusted as nearly as possible to the requirements of the load, and the results are generally good. In the great Niagara plant the governor is situated on the floor of the power house, nearly 140 feet above the wheels. It is a very sensitive mechanical relay, in which the motion of a pair of fast running fly balls puts into operation a brake-tightening mechanism, which in its turn permits power to be transferred from pulleys driven from the turbine shaft through a pair of dynamometer gears to the system of gearing that works the balanced gate at the end of the lever system 140 feet below the governor. This governor was guaranteed to hold the speed constant within 2 per cent. under ordinary changes of load, and to limit the speed variation to 4 per cent. for a sudden change of 25 per cent. in the load. Fig. 174 gives a good notion of the principles of this apparatus, which is doing good service. The Replogle governor is an electro-

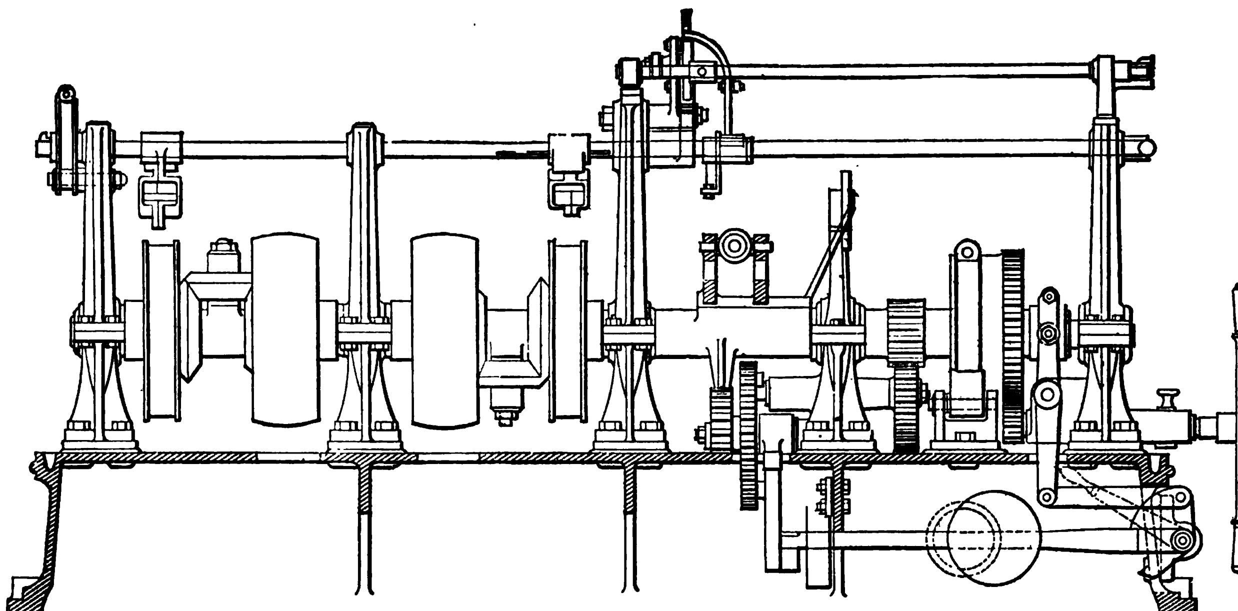


FIG. 174.

mechanical relay shown in Fig. 175, which exhibits its general arrangement very well. The work done by the fly balls is very trifling and the mechanism is both sensitive and powerful. Fig. 176 shows its performance in governing a railway load

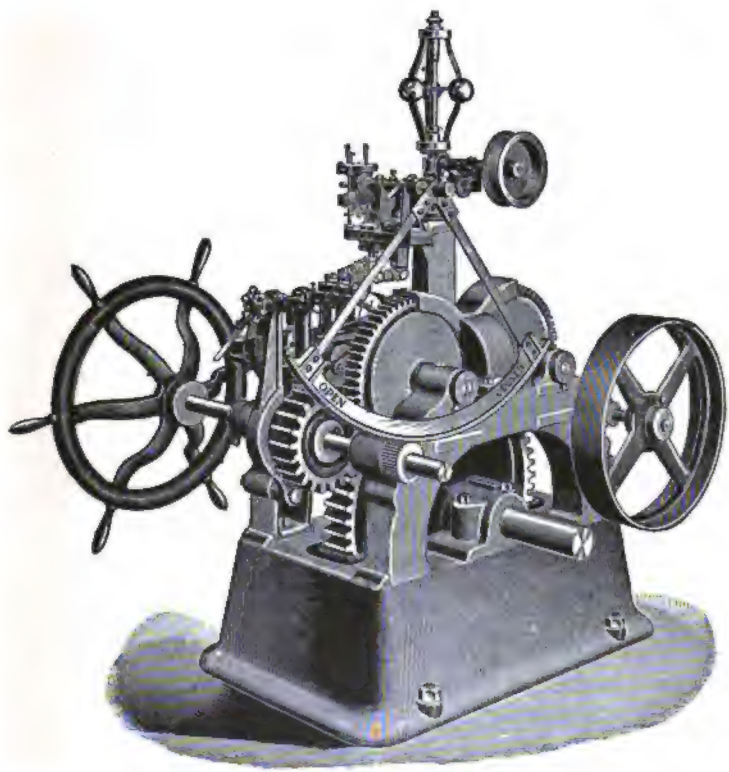


FIG. 175.

under conditions of unusual severity. As in Fig. 173, 20 minutes of operation are plotted and the maximum variation from 105 revolutions per minute, the normal speed, is less than 10 revolutions, and that variation lasted less than 20 seconds and was due to the opening of the circuit-breaker. Such work is quite good enough to meet all ordinary conditions.

To a very different type of mechanism belongs the differential governor shown in Fig. 177. It has been applied widely to

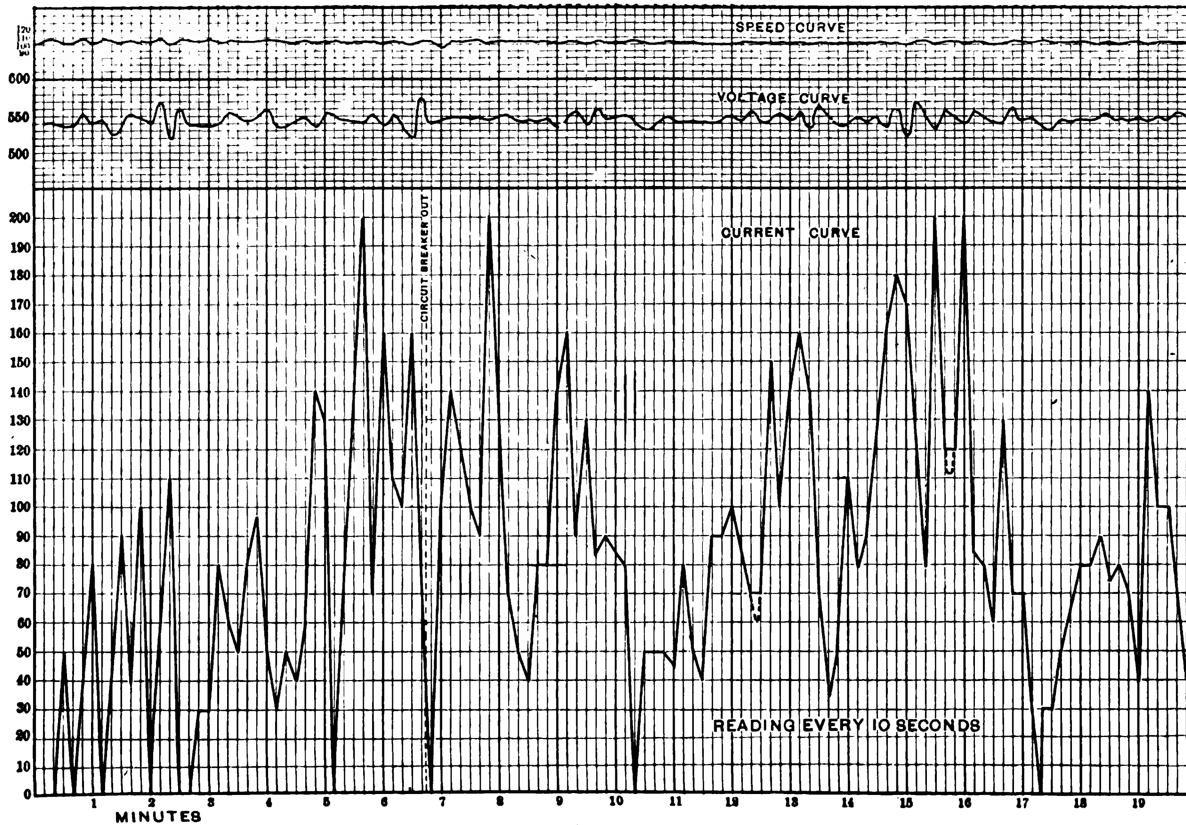

SPEED CURVE
VOLTAGE CURVE
CURRENT CURVE
CIRCUIT BREAKER OUT
READING EVERY 10 SECONDS
MINUTES
600
550
500
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
1
2
3
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FIG. 176.

the governing of Pelton impulse wheels, with very excellent results. The principle involved is very simple. Two bevel gears, each carrying on its shaft a pulley, are connected by a pair of bevel gears on a crosswise shaft, forming a species of dynamometer gearing. Normally the main gears are driven in opposite directions, the one at a constant speed by a special source of power, the other from the shaft to be governed. So long as the speeds of these wheels are exactly equal and

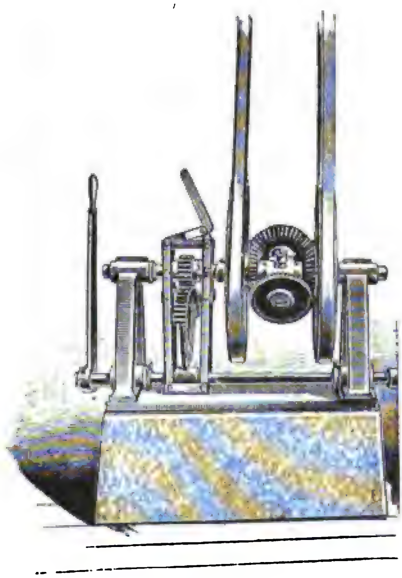


FIG. 177.

opposite, the transverse shaft remains stationary in space and the gate moving mechanism attached to it is at rest. When, however, the working shaft changes speed under the influence of a change in load, the transverse shaft necessarily moves in one direction or the other and keeps on moving until the working shaft gets back to speed.

In practice the main difficulty is to hold the constant speed necessary for one of the bevel gears, and the governor works admirably or badly as this constancy is or is not maintained. A heavy fly wheel on the constant speed side is desirable, and its motive power should be quite independent of the main

drive. Perhaps the best result is obtained by using a second, small, differential governor to hold the speed uniform at the main governor. With the high heads and balanced deflecting nozzles usual in Pelton wheel practice, this form of governor is very sensitive and does not hunt noticeably, owing to the small inertia of the moving parts. It gives good regulation under all conditions except extreme variations of load, where the wheel is loaded beyond the power of the jet to enforce prompt recovery of speed, and is singularly well suited to the conditions under which Pelton wheels are generally used.

In all hydraulic governing it should be remembered that the same results cannot be expected under all conditions. Moderate heads, short inlet pipes and gates directly at the wheel are the most favorable conditions. Very high and very low heads are hard to govern, the former on account of the great pressures that must be managed, and the latter on account of great inertia and the consequent large power that must be applied to work the gates promptly. Long head pipes give trouble on account of the great energy of the moving water which must be controlled, and gates far away from the wheel give necessarily sluggish regulation. Under favorable circumstances with the best modern governors the speed of water wheels can be held almost or quite as steady as the speed of a well governed engine. One must not, however, expect such a result indiscriminately in all cases, nor be surprised if the first governor tried does not quite meet expectations.

CHAPTER VIII.

HYDRAULIC DEVELOPMENT.

So much electrical transmission work depends on the utilization of water powers that it is worth while briefly to consider the subject of developing natural falls for such use. The subject is a large one, quite enough to fill a volume by itself, and the most that can be done here is to point out the salient facts and put the reader in possession of such information as will enable him to avoid serious blunders and to take up the subject intelligently.

Natural water powers of course vary enormously in their characteristics. In our own country, where water power is very widely distributed, we find three general classes of powers, often running into each other but still sufficiently distinct to cause the methods of developing them to be quite well defined.

By far the best known class of powers are those derived from the swift rivers that are found in New England and other regions in which the general level of the country changes rather rapidly. They flow through a country of rocky and hilly character, and large or small, are still swift, powerful streams, with frequent rapids and now and then a cascade. Such rivers are generally fed to no small extent by springs and lakes far up toward the mountains, and catch in addition the aggregated drainage of the irregular hill country through which they flow. Types of this class are the Merrimac and the Androscoggin among the New England rivers, the upper Hudson, and many others. Another and quite different class of powers are those derived from the slow streams that flow through a flat or rolling alluvial country—the Mississippi valley and the lowlands of the Southern Atlantic States. Although possessed of many tributaries that spring from among the mountains, the great basins which they drain form the main reliance of rivers of this kind—immense areas of fertile country the aggregated rainfall of which supports the streams.

Finally, there are many fine water powers that come from mountain streams, fed from little mountain springs, from the melting of the winter snows and the drainage of heights which the snow never deserts, and from the rain gathered by mountain gorges.

These mountain rivers often furnish magnificent powers, easy and cheap to develop, but very variable. In summer the stream may dwindle to a mere brook, while in spring, from the combined effect of rains and melting snow, it will suddenly increase even many thousand fold, becoming a tremendous torrent that no works built by man can withstand. The available heads are often prodigious, from a few hundred to more than a thousand feet, and the volume of water may seem at first sight absurdly small, but when, as in the Fresno (Cal.) plant to be described later, each cubic foot flowing per second means 140 mechanical HP delivered by the wheels, large volume is needless.

Upland rivers like those common in New England seldom give opportunity for securing high heads. Most of the powers developed show available falls ranging from 20 to 40 feet. Unless the stream has considerable volume, such low heads do not yield power enough to serve anything but trivial purposes—only two or three HP per cubic foot per second. Upland rivers, however, furnish the great bulk of the water power now utilized, for they furnish fairly steady and cheap power under favorable conditions. Although subject to considerable, sometimes formidable, freshets when the snow is melting or during heavy rains, they are generally controllable without serious difficulty.

Lowland streams seldom offer anything better than very low heads, rarely more than 10 to 15 feet, and consequently demand an immense flow to produce any considerable power. They are, however, as a class rather reliable. The size and character of the drainage basin makes extremely low or extremely high water rare, and only to be caused by very great extremes in the rainfall. Such streams furnish a vast number of very useful powers of moderate size, forming a large aggregate but seldom giving opportunity for any striking feats of hydraulic engineering, at least in our own country, where fuel is generally cheap.

In taking up any hydraulic work with reference to electrical power transmission, or any other purpose, in fact, the first necessary step is to make a sort of *reconnoissance*, to ascertain the general topography of the region, the available head, and the probable flow. The first two points are generally easy to determine from existing surveys or by a brief series of levels, the last named requires a combination of educated judgment and careful engineering. The facts are not really very difficult to get at, but guesswork is emphatically out of order and hearsay evidence even more worthless than usual. The author has seen more than one mighty torrent dwindle into a trout brook when looked at through untinted spectacles.

The only way to find out how much flow is available is to measure it carefully, if it has not already been measured in a thorough and trustworthy manner—not once or twice or a dozen times, but weekly or, better, daily for an entire season at least; the more thoroughly the better. A knowledge of the absolute flow at one particular time is interesting, but of little value compared with a knowledge of the variations of flow from month to month, or year to year.

Such a series of measurements tells two very important things—first, the minimum flow, which represents the maximum power available continuously without artificial storage of water; and second, the aggregate flow during any specified period, which shows the possibilities of eking out the water supply by storage.

The methods of measurement are comparatively simple. For small streams the easiest way is to construct a weir across the stream and measure the flow over a notch of known dimensions in this weir. Such a temporary dam should be tight and firmly set, and high enough to back up the water into a quiet pool free from noticeable flow except close to the edge of the weir. There should be sufficient fall below the bottom of the notch in the weir to give a clear and free fall for the issuing water—say two or three times the depth of the flow over the weir itself.

Fig. 178 shows clearly the general arrangement of a measuring weir. Here *A* shows the end supports of the weir, here composed of a single plank, while *B* is the lower edge of the notch through which the water flows. This edge *B*, as well as

the sides of the notch, should be chamfered away to a rather sharp edge on the upstream side, which must be vertical. Back some feet from the weir so as to be in still water should be set firmly a post *E*, the top of which is on exactly the same level as the bottom of the weir notch *B*. *D* shows this level, while the line *C* shows the level of the still water. The quantities to be exactly measured are the length of the notch *B* and the height from the level of the edge of *B* to the normal

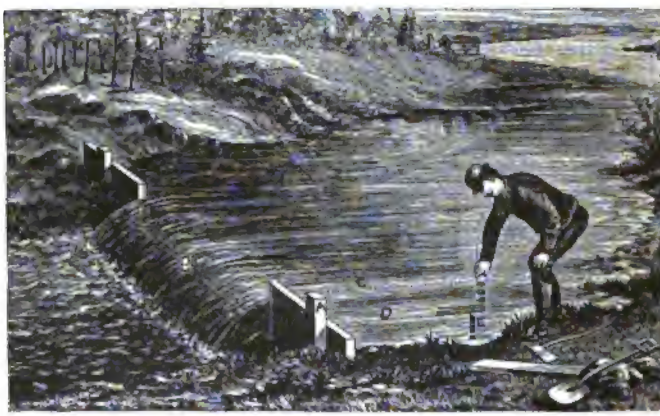


FIG. 178.

level surface of the water in the pool. This can be done generally with sufficient accuracy by holding or fixing a scale on the top of the post *E*. If we call the breadth of the notch b, and this height h, both measured in feet, the flow in cubic feet per minute is

$$Q = 40\, c\, b\, h\, \sqrt{2\, g\, h}$$

Here g is 32.2 and c is the "coefficient of contraction," which defines the ratio of the actual minimum area of the flowing jet to the nominal area $b\,h$.

This coefficient varies slightly with the width of the notch as compared with the whole width of the weir dam. Calling this w, the value of c is approximately

$$c = 0.57 + 10\,\frac{b}{w}.$$

This gives $c = .62$ for a notch half the width of the weir and $c = .67$ for the full width of the weir. For notches below one-quarter the width of the weir the values of c become somewhat uncertain, and as a rule b should be over half of w. Further, the notch should not be so wide as to reduce the water flowing over it to a very thin sheet. It is best to arrange the notch so that the depth of water h may be anywhere a tenth to a half of b. For purposes of approximation weir tables are sometimes convenient. These give usually the flow in cubic feet per minute corresponding to each inch in width b, for various values of h. Such a table, condensed from one used by one of the prominent turbine makers, is given below. Where quite exact measurement is required the constant c should be determined from the actual dimensions and a working table deduced from it.

TABLE FOR WEIRS.

INCHES AND FRACTIONS DEPTH ON WEIR.	0	¼	½	¾
1	0.40	0.56	0.74	0.97
2	1.14	1.36	1.59	1.84
3	2.09	2.36	2.64	2.93
4	3.22	3.53	3.85	4.17
5	4.51	4.85	5.25	5.56
6	5.92	6.30	6.68	7.07
7	7.46	7.87	8.28	8.70
8	9.12	9.55	9.99	10.43
9	10.88	11.34	11.80	12.27
10	12.75	13.23	13.72	14.21
11	14.71	15.21	15.72	16.24
12	16.76	17.28	17.82	18.35
13	18.89	19.44	20.00	20.56
14	21.12	21.68	22.26	22.83
15	23.42	24.01	24.60	25.19
16	25.80	26.41	27.02	27.63
17	28.26	28.88	29.51	30.14
18	30.78	31.43	32.07	32.73

Cubic feet per minute per inch of width.

West of the Rocky Mountains a special system of measuring water by "miner's inches" has come into very extensive use. It originated in the artificial distribution of water for mining and irrigating purposes, and has since extended to a conventional measurement for streams. The miner's inch is a unit

of constant flow, and varies somewhat from State to State, its amount being often regulated by statute in various States: It is the flow through an aperture 1 inch square under a specified head, frequently 6 inches. The method of measurement is shown in Fig. 179. The water is led into a measuring box closed at the end except for an aperture controlled by a slide. The end board is $1\frac{1}{4}$ inch thick, and the aperture is 2 inches

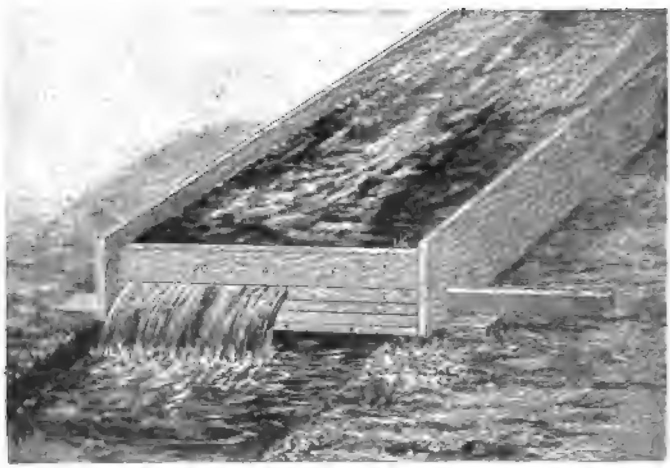


FIG. 179.

wide, its bottom is 2 inches above the bottom of the box, and its centre 6 inches below the level of the water. Each inch of length of the aperture then represents 2 miner's inches. Under these conditions the flow is 1.5 cubic feet per minute for each miner's inch. Under a $4\frac{1}{2}$ inch effective head, which is extensively used in Southern California and the adjacent regions, the miner's inch is about 1.2 cubic feet (9 gallons) per minute.

For streams too large to be readily measured by the means already described, a method of approximation is applied as follows:

Select a place where the bed of the stream is fairly regular and take a set of soundings at equal intervals, *a*, *b*, *c*, *d*, Fig. 180, perpendicular to the direction of flow, using a staff rather than a sounding line, as it can more easily be kept perpendicu-

lar. Ascertain thus the area of flow. Then establish two lines across the stream say 100 feet apart and nearly equidistant from the line of soundings. Then throw floats into the stream near the centre and time their passage across the two reference lines. This establishes the velocity of the flow across the measured cross section. As the water at the bottom and sides of the channel is somewhat retarded, the average velocity is generally assumed to be 80 per cent. of that measured as above in the middle of the stream.

The more complete the data on variations of flow, the better. The most important point to be fixed is the flow at

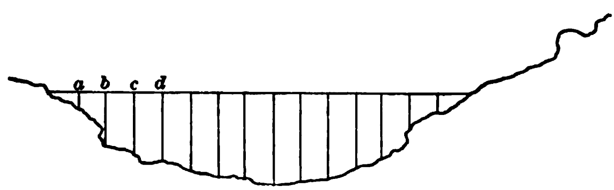


FIG. 180.

extreme low water, both in ordinary seasons and seasons of unusual drought. Except on very well-known streams previous data on this point are generally not available. The flow should therefore be measured carefully through the usual period of low water during at least one season. From the minimum flow thus obtained there are various ways of judging the minimum flow in a very dry year. Sometimes certain riparian marks are known to have been uncovered in some particular year, and the relative flow can be computed from the difference thus established. Again, the records of a series of years may be obtained from a neighboring stream of similar character, and the ratio between ordinary and extraordinary minima assumed to be the same for both. This assumption must be made cautiously, for neighboring streams often are fed from sources of very different stability.

Failing in these more direct methods, recourse may be taken to rainfall observations. For this purpose the rainfall in the basin of the stream should be measured during the continuance of the observations on flow. By noting the effect of

known rainfall on the flow of the stream, one can make a fairly close estimate of the flow in a very dry year in which the rainfall is known by months, or for an assumed minimum rainfall. In a similar way can be ascertained the probable high water mark, record of which is often left by *débris* on the banks.

In a fairly well-known country the conditions of flow can be approximated by reference to rainfall alone. The area drained by the stream down to the point of utilization can be closely estimated. If rainfall observations in this district are available, or can be closely estimated from the results at neighboring stations, one may proceed as follows: The total water falling into the basin is 2,323,200 cubic feet per square mile for each inch of rainfall. Only a portion of this finds its way into the streams, most of it being taken up by seepage, evaporation, and so forth. The proportion reaching the streams varies greatly, but is usually from .3 to .6 of the whole. If this proportion is known from observations on closely similar basins and streams the total yearly flow can be approximated, and if the distribution of flow on a similar stream is known, one can make a tolerable estimate of the amount and conditions of flow in the stream under investigation.

This process is far from exact, since the proportion of the total water which is found in the streams varies greatly from place to place, and with the total rainfall in any given week or day. The sources of loss do not increase with the total precipitation, and the only really safe guide is regular observation of the rainfall and the flow during the same period.

In some streams, generally in dry climates, no small part of the flow is in the strata underlying the apparent bed of the stream during the dry season, and can be in part, at least, captured by carrying down the foundations of the permanent works.

When the flow has been ascertained the available HP is easily computed. The practicable head can be easily determined by a little levelling. If H is this head in feet and Q the flow in cubic feet per minute then the theoretical HP of the stream is

$$\mathrm{HP} = \frac{62.4\, H\, Q}{33{,}000}.$$

The mechanical HP obtained by utilizing the stream in water wheels is this total amount multiplied by the efficiency of the wheels, usually between .75 and .80. In many streams the available head is limited by the permissible overflow of the banks as determined by the rights of other owners, or by danger of backing up the stream to the detriment of powers higher up. These conditions must be determined by levelling.

In streams of small volume carried through pipe lines the effective head is diminished by friction in the pipes. This loss has already been discussed in Chapter II.

It often happens that there is so great a difference between the normal flow of a stream during most of the year and its minimum flow during a few weeks as to make it highly desirable to store water by impounding it, so as to help out the sometimes scanty natural supply. With mountain streams under high head this is frequently quite easy. Even when it is impracticable to impound enough to help out during the whole low water period it is sometimes very useful to impound enough to last for a day or two in case of necessary repairs to the regular head works.

A certain reservoir capacity is quite necessary so as to permit the storage of water at times of light load for utilization at times of heavy load. This process is carried out on a vast scale on the New England rivers, where the water, used during the day in textile manufacturing, is stored in the ponds at night as far as possible. While electric transmission plants do not offer the same facilities for storage, since they generally run day and night, the application of the same process would often greatly increase their working capacity and greatly lower the fixed charges per hydraulic HP. Such storage is especially valuable in cases where the water supply is limited, as it often is in plants working under high heads. Every cubic foot of water is then valuable and should be saved whenever possible. Regulation by deflecting nozzles, which is very generally employed in this class of plants, is particularly objectionable on the score of economy, and ought to be replaced by some more efficient method.

As an example of what can be done with storage under high heads, it happens that at 650 feet effective head one mechani-

cal HP requires almost exactly one cubic foot of water per minute at 80 per cent. wheel efficiency. For a 500 HP plant, then, the water required is 30,000 cubic feet per hour.

One can store 43,560 cubic feet per acre per foot of depth, so that a single acre 10 feet deep would store water enough to operate the plant at full load for 14½ hours, or under ordinary conditions of load for a full day. If the flow in the stream were only 15,000 cubic feet per hour in time of draught, the acre would yield two days supply and 15 acres would carry the plant for a month. Such storage is common enough in irrigation work, and is capable of enormously increasing the working capacity of a transmission plant, even at a head much less than that mentioned.

With only 100 feet available head it is comparatively easy to impound water enough to assist very materially in tiding over times of heavy load and in increasing the available capacity. A survey with storage capacity in view should be made whenever storage is possible, and the approximate cost of storage determined. A little calculation will show in how far storage will pay.

In general the utilization of a water power consists in leading the whole or a part of a stream into an artificial channel, conducting it in this channel to a convenient point of utilization, and then dropping it back through the water wheels into the channel again, usually via a tail race of greater or less length.

Except where there is a very rapid natural fall a substantial dam is necessary, which backs up the water into a pond, usually gaining thus a certain amount of head, whence the water is led in an open canal to some favorable spot from which it can be dropped back into the channel at a lower level. The canal may vary in length from a few rods to several miles, according to the topography of the country. The tail race leading the water from the wheels back to the stream is short, except in rare instances like the great Niagara plant. In this case, shown somewhat roughly in Fig. 181, the usual construction was reversed. To obtain ample clear space for manufacturing sites and the like, the water was utilized by constructing above the cataract an artificial fall at the bottom of which the wheels were placed. From the bottom of this huge shaft, cut 178 feet

deep into the solid rock, the water is taken back into the river through a tunnel 7,000 feet long, which constitutes the tail race. The water is taken directly from the river into the canal without even a deflecting dam.

In the case of mountain streams having a very rapid fall the dam is often quite insignificant, serving merely to back up the water into a pool from which it may be conveniently drawn, or even to deflect a portion of the water for the same purpose. In such cases the water is usually carried in an iron or steel

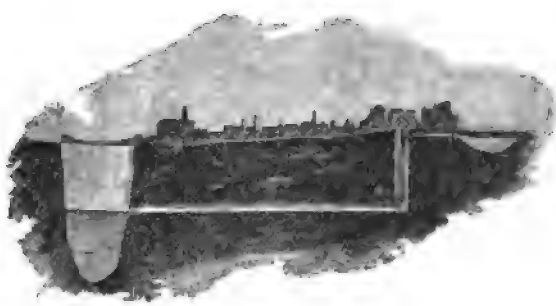


FIG. 181.

pipe, following any convenient grade to the bottom of the fall chosen, at which point its full pressure becomes available.

In ordinary practice at moderate heads the volume of water has to be so considerable for any large power as to make a long canal very expensive. Further, it usually happens that the topography of the country is such as to make it very difficult to gain much head by extending the canal. Thus the points chosen for power development must be those where there is a rather rapid descent for a short distance—falls or considerable rapids. Then a dam of moderate height gives a fair head by simply carrying the canal to a point where the water can be readily returned to the stream below the natural fall. The more considerable this fall the less need for an elaborate dam, which may become simply a means of regulating the flow of water without noticeably raising the head.

A fine example of this sort of practice is shown in Fig. 182, which shows a plan of the hydraulic development of the falls of the Willamette River at Oregon City, Ore. The river at this point gives an estimated available HP of 50,000 under 40

feet head. The stream plunges downward over a precipitous slope of rough basalt, and the low dam which follows the somewhat irregular shape of the natural fall is hardly more than an artificial crest to guide the water toward the canal on the west bank of the stream. This canal has recently been widened, and both constructions are shown in the figure. The fine three-phase transmission plant of the Portland General Electric Company now faces on the new canal wall near the section G. At the end of the canal downstream a series of locks lead down to

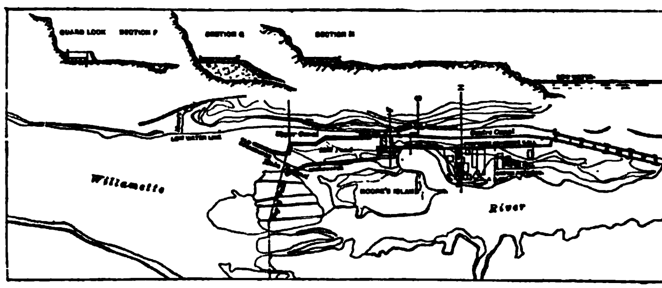


FIG. 182.

the lower river, making the falls passable for river craft. Only a small part of the available power is as yet used.

Almost every river presents peculiarities of its own to the hydraulic engineer. Generally the dam is a far more prominent part of the work than at Oregon City, and adds very materially to the head. Choosing a proper site for the dam, and erecting a suitable structure, requires the best skill of the hydraulic engineer. Bearing in mind that the function of a dam is to merely retain and back up the flowing water, it is evident that it may be composed of a vast variety of materials put together in all sorts of ways. Stone, logs, steel, all come into play combined with each other and with earth.

The character of the river bed which furnishes the foundation is a very important factor in determining the material and shape of the dam used. When the bed is of rock or that hard packed rubble that is almost as solid, a well-built stone dam is the best, as it is also the costliest construction. For such work the way is cleared by a coffer dam and the masonry is laid, if possible, directly upon the bedrock. When the bottom

is hard pan a deep foundation for the masonry is almost as good as the ledge itself, while on a gravel bottom sheet piling is sometimes driven and the stone work built around it. The ground plan is very frequently convex upstream, giving the effect of an arch in resisting the pressure of the water. Fig. 183 shows a section of a typical masonry dam, built over sheet piling in heavy gravel. This particular dam is 22′ 6″ high and nearly 300 yards long. The coping is of solid granite slabs a foot thick. Below the dam lies the usual apron of timber and concrete, with timber sills anchored into the dam

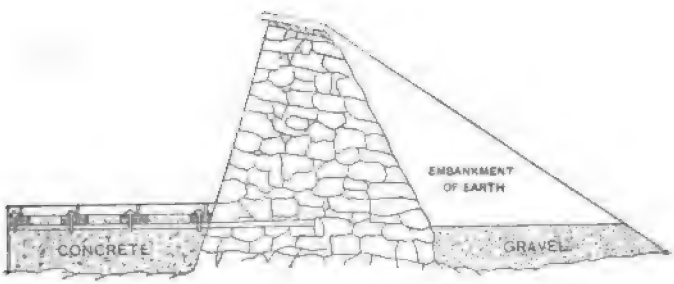


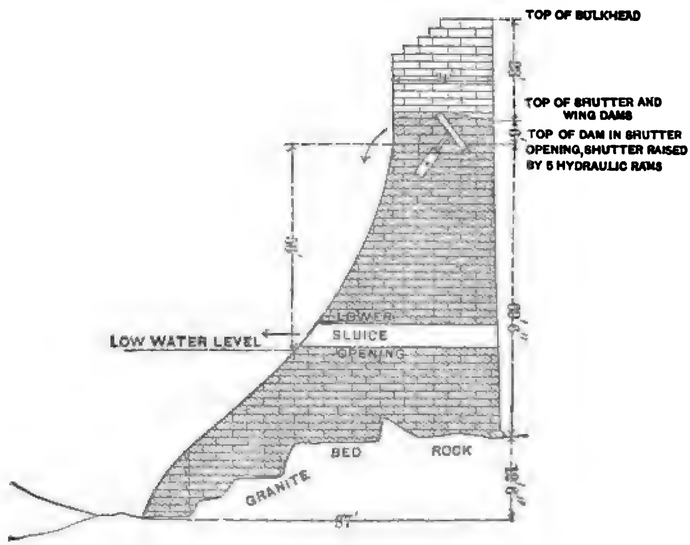
FIG. 183.

itself. The flooring of the apron, of 12″ × 12″ timbers laid side by side, is bolted to the foundation timbers laid in the concrete. The purpose of this apron, as of such structures in general, is to prevent undermining of the dam by the eddies below the fall.

A still finer example of the masonry dam is shown in Fig. 184—the great dam of the Folsom Water Power Company across the American River at Folsom, Cal. It is built of hewn granite quarried on the spot, and is founded on the same ledge from which the material was taken. The abutments likewise are built into the same ledge. On the crest of the dam proper is a huge shutter or flash board, 185 feet long, capable of being swung upward into place by hydraulic power. When thus raised it gives an added storage capacity of over 13,000,000 cubic yards of water in the basin above. This dam furnishes power for the great Folsom-Sacramento transmission, and it ranks as one of the finest examples of hydraulic engineering in existence. Including the abutments it is 470 feet long, and the crest of the abutments towers nearly 100 feet

above the foundation stones. Its magnificent solidity is not extravagance, for the American River carries during the rainy season an enormous volume of water, filling the channel far over the crest of the dam when at its maximum flow. There are few streams where greater strains would be met.

While these masonry dams are splendidly strong and enduring, they are also very expensive, and hence unless actually



SECTION OF DAM
{ THRUST —1911 TONS. }
{ STABILITY—7979 TONS. }
Containing 37,000 cu. yards of masonry.

FIG. 184.

demanded for some great permanent work are less used than cheaper forms of construction. In many situations these are not only cheaper in first cost, but even including depreciation. There are many forms of timber dam which have given good service for many years at comparatively small expense. Of such dams, timber cribs ballasted with stone are probably under average conditions the best substitute for solid masonry. These crib dams when well built of good materials are very durable and need few and infrequent repairs. Some such dams, replaced after twenty-five or thirty years in the course of changing the general hydraulic conditions, have shown timbers

as solid as the day they were put down, and capable of many years' further service.

A fine example of such construction is the dam of the Concord (N. H.) Land & Water Power Company at Sewall's Falls on the Merrimac. A section of this structure is shown in Fig. 185. The foundation is in the main gravel, in which the dam is made secure by sheet piling and stone ballast. The structure is essentially a very solid timber crib with a very long apron. The total head is 23 feet, of which more than half is due to the dam, as shown in the levels. The apron is armored with five-sixteenths inch steel plate, the better to withstand the bombardment of stray logs to which it is sometimes subjected. The abutments are of granite. It has proved very serviceable, having successfully withstood several tremendous freshets with no damage save some undermining of one of the abutments, which has been repaired with crib work. Considering the character of the river bed, this dam is probably as reliable as one of masonry, and its cost was little over half that of a masonry dam.

For small streams these ballasted timber dams are admirable, and little more is needed in most cases.

The canals leading the water to the wheels are of construction as varied as the dams, depending largely on the nature of the ground. Sometimes they are merely earthwork, oftener they are lined with timber, concrete, or masonry. Canal construction is a matter to be decided on its merits by the hydraulic engineer, and very little general advice can be given.

For very high heads, canals and sluices are almost universally replaced by iron or steel riveted pipe taken by the nearest route to the wheels below. This practice has been in general use on the Pacific coast and has given admirable results. The pipes are asphalted inside and out to prevent corrosion, and some pipe lines have been in service for a quarter of a century without marked deterioration. Large pipes and those for very heavy pressures are usually made of mild steel. The pipes are customarily made in sections for shipment, from 20 to 30 feet long, and the slip joints are riveted or packed on the ground. For transportation over very rough country and for very large pipes, the sections may be no more than 2 or

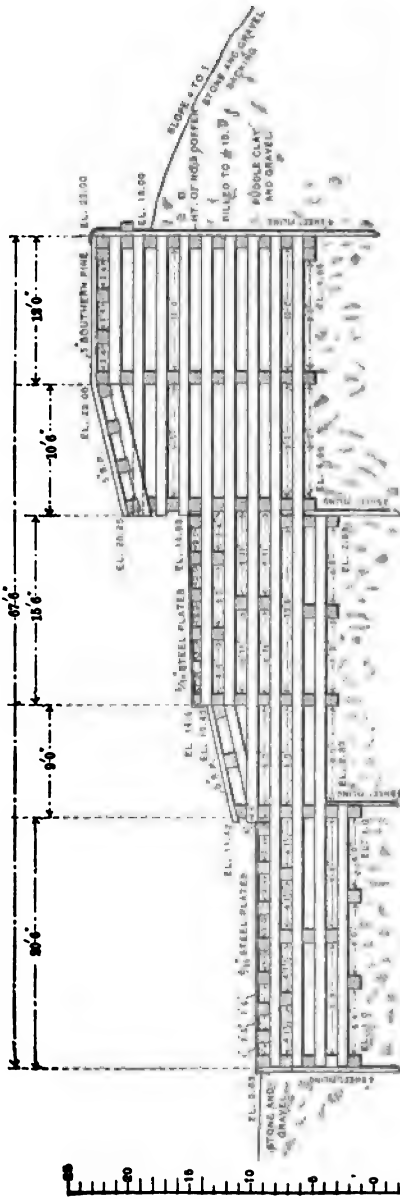


FIG. 185.

3 feet long. The joints are then asphalted on the ground. Fig. 186 shows several of these short sections joined together, exhibiting the nature of the riveting and the terminal slip joint.

In running such a pipe line it is usually taken as straight as possible, and is laid over, on, or under the ground as occasion requires, usually on the surface, conforming to its general contour. In long lines the upper end is usually larger and

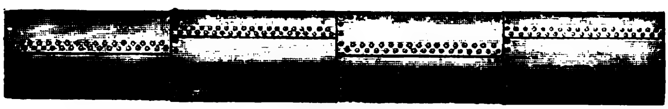


FIG. 186.

thinner than the lower, which has to withstand the heavy pressure. Fig. 187, which is a profile to scale of the pipe line of the noted San Antonio Cañon plant in southern California, gives an excellent idea of good modern practice in this sort of work. There is here a total fall of about 400 feet in a distance of 2,000 feet. The main pipe is 30″ in diameter, and the steel is of the gauges indicated on the various sections. At the crests of two undulations, air valves are placed to ensure a

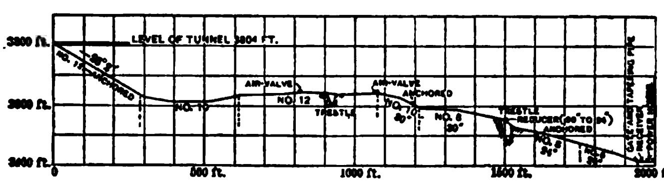


FIG. 187.

solid and continuous column of water in the pipe. The last 450 feet of pipe is reduced to 24″ and the gauge of steel is somewhat heavier. The total length of the pipe line is 2,370 feet. To protect the pipe against great changes of temperature it was loosely covered with earth, rock, and brush whenever possible. At two sharp declivities the pipe was anchored to the rock.

The general method of anchoring on a steep incline is shown

in Fig. 188. In this case the slip-joint is simply calked, and where consecutive sections are at an angle, a short sleeve is fitted over the joint and lead is run in as shown in the cut. Often a packed slip joint is used very freely, thereby gaining

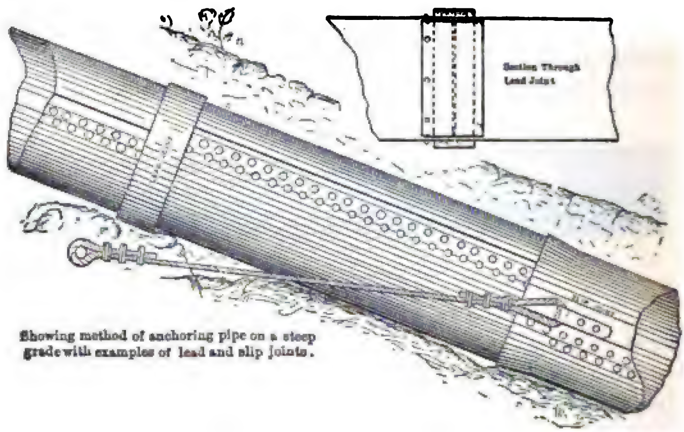


FIG. 188.

in flexibility, and riveted joints may be only used occasionally. The line is generally started from the lower end and the joints or the whole interiors of the sections asphalted as they are laid. The following table gives the properties of steel hydraulic pipe of the sizes in common use, and double riveted:

Diameter in inches......	10	12	14	16	18	20	24	30	36	42
Area in square inches...	78	113	153	201	254	314	452	706	1,017	1,385
Cubic feet per minute at three feet per second..	100	142	200	255	320	400	570	890	1,300	1,760
Weight in pounds per foot..................	19.25	22.75	26	29.5	34	36.5	43.5	54	67	74.5
Safe head in feet........	900	750	650	560	500	450	375	300	150	135
Change in above for each gauge number........	100	90	80	70	60	55	45	35	20	20

The pipe is assumed to be of No. 10 gauge steel, and the changes in safe head are of course approximate only, but hold with sufficient exactness for a variation of two or three gauge numbers. It is better to use a pipe too thick than one too

thin, and to use extra heavy pipe at bends. Where the ground permits, the water can often be carried to advantage in a flume or ditch, and then dropped through a comparatively short pipe line. For heads approaching or surpassing 1,000 feet it is probably safer to use lap-welded tube for the lower portion of the run. In every case suspended sand must be kept out of the water, else it will cut the wheels and nozzles like a sand blast. When one remembers that under 400 feet head the spouting velocity of the water is about 160 feet per second, the need of this precaution is evident. A large settling tank is usually provided at the head works, spacious and deep enough to let the pipe draw from the clear surface water. At its lower end the pipe line terminates in a receiver—a heavy cylindrical steel tank of considerably larger diameter than the pipe proper, from which water is distributed to the wheels.

On very high heads a relief valve is often attached near the receiver to avert danger from a sudden increase in pressure in the pipe, such as might be caused by some sudden obstruction at the gate.

This pipe line method of supply is considerably used for turbines of moderate size on heads as low as 75 to 100 feet, in cases where the natural fall of the stream is rather sudden. It really amounts to a considerable elongation of the iron penstock which is in common use. Whenever there is a sharp declivity in difficult country, piping is often easier and cheaper than constructing a flume or canal. In such situations the pipes may be 5 or 6 feet in diameter or even more, and being under very moderate pressure, may be comparatively light and cheap.

In cold climates ice is one of the difficulties most to be dreaded in hydraulic work. In high pressure pipe lines there is little to fear, for fast-running water does not freeze easily and the pipes can generally be readily covered, as in the San Antonio Cañon plant, enough to prevent freezing. Large canals simply freeze over and the interior water is thus protected. But in cold climates there is considerable danger of the so-called anchor-ice. This is, in extremely cold weather, formed on the bed and banks of rapid and shallow streams. The surface does not freeze, but the water is continually on the point of freezing and flows surcharged with fine fragments

of ice that pack and freeze into a solid mass with the freezing water rapidly solidifying about it. When in this condition it rapidly clogs the strainers that protect the penstocks, and even the wheel passages themselves.

The best protection against this is a deep, quiet pond above the dam, in which no anchor ice can form, and which will attach to its own icy covering any ice fragments that drift down from above.

The most dangerous foe of hydraulic work is flood. The precautions that can be taken are, first, to have the dam and head-works very solid, and second, so to locate them if possible as to have an adequate spillway over which even a very large amount of surplus water can flow without endangering the main works. If a pipe line is used it must be laid above high water mark, else the first freshet will probably carry it away. The power station must likewise be out of reach even of the highest water.

Closely connected with the subject of floods is that of variable head, which in many streams is a constant source of difficulty. In times of flood the extra height of the water above the dam is generally useless, while the tail water rises and backs up into the wheels, cutting down their power and speed, often very seriously. This matter has already been discussed in Chapter VII., in so far as it is connected with the arrangement of the turbines. At very high heads this trouble vanishes, as no possible variation of the water level can be a considerable fraction of the total head.

The most delicate questions involved in hydraulic development are those connected with variable water supply. Having ascertained as nearly as possible the minimum flow, the minimum natural continuous supply of power is fixed, but it remains to be determined how the water in excess of this shall be utilized, if at all.

Three courses are open for increasing the available merchantable power. First, water can be stored to tide over the times of small natural supply. Second, a plant can be installed to utilize what water is available for most of the year and can be curtailed in its operation during the season of low water. Third, the service can be made continuous by an auxiliary steam plant in the power station. Storage of water can

obviously be used in connection with either of the other methods.

Under very high heads storage is generally worth the while if the lay of the land is favorable. This of course means a dam, but not necessarily a very high or costly one. If possible the storage reservoir should be a little off the main flow of the stream so as to escape damage from freshets. Reverting to our previous example of storage, suppose we have 500 HP available easily for nine months of the year, but a strong probability of not over 250 HP for the remaining three months. We have already seen that under these circumstances 15 acres flooded 10 feet deep will keep up the full supply for a month. If say 50 acres can be thus flooded, the all-the-year-round capacity of the plant will be doubled. In the mountainous localities where such heads are to be found, land has usually only a nominal value, and impounding the equivalent of this amount of water is frequently practicable. If it can be done at say a cost of $75,000, the annual charge per HP stored, counting interest and sinking fund at 10 per cent., will be $30, and the investment would generally be a profitable one. If the storage cost $100,000, the annual charge would be $40, and this would not infrequently be well worth the while, when power could be sold for a good price.

At lower heads the annual charge per HP stored would be considerably greater for the same total expenditure. Sometimes, however, storage capacity can be much more cheaply gained for both high and low heads, at for instance not more than half the charge just mentioned. The matter is always worth investigating thoroughly when there is doubt about supplying the power market with the natural flow. The points to be looked into are the nature and extent of the low water period, and the cost of developing various amounts of storage capacity. Sometimes the period of extreme low water is much shorter than that assumed, and storage is correspondingly cheaper.

There are some cases in which it is possible to supply customers with power for nine or ten months in the year, falling back on the individual steam plants in the interim. When transmitted power can be cheaply had, it is worth while for the power user who is paying, say $100 per HP per year for

steam power to take electric power at $50 per HP per year for nine months, and to use steam the other three months. Certain industries, too, are likely to be comparatively inactive in midsummer, or may find it worth while to force their output during the months when cheap power is obtainable, and shut down or run at reduced capacity when the power is unavailable. This is a matter very dependent on local conditions, and while the demand for such partial power supply is generally limited, there are many cases in which it would be advantageous for all parties concerned. In some mountainous regions, winter is the season of low water owing to freezing, and various industries are suspended which may be profitably supplied with power when the winter unlocks its gates.

Eking out the water supply by an auxiliary steam power station is likewise not of general applicability, but sometimes may prove advantageous. It is most likely to prove useful in localities where a steam power plant would pay by virtue of the economy due to production on a large scale and distribution to small users. Cheap water power a large part of the year then abundantly justifies adjunct steam power when necessary. The moral effect of continuous power supply is valuable in securing a market. Whether such a supply is profitable depends on the ratio between the cost of water power and the cost of steam power. And it must not be forgotten that steam power for two or three months in the year is relatively much more costly than continuous power.

The general charges are the same, although labor, coal, and miscellaneous supplies decrease nearly as the period of operation. Consequently, since there is this large fixed item, amounting to from 20 to 40 per cent. of the total annual cost, the cost of power in a plant operated only three months will be relatively at least 50 per cent. greater than if it were in constant operation. There must be a large margin in favor of water power to justify this auxiliary use of steam, unless the latter would pay on its own account, as for instance in a plant used largely for lighting, which would be the most profitable kind of electric service were there a sufficiently large market. Moreover a large proportion of lighting automatically relieves the load in midsummer, the most usual time of low water.

The actual economics of such a question can only be deter-

mined after a thorough examination of local costs, since the costs of both steam and water power have a wide range.

Steam power on a 12 hour basis at steady full load varies according to the size and kind of plant, cost of fuel, and so forth, from a little under $20 per HP year to $125 or more, with an increase of one-third to one-half in case of variable loads. Water power rents for from $10 to $60 or more per HP year, and may cost to develop anywhere from $20 to $150 per HP. At the former price it is cheaper than steam under any circumstances, at the latter it is dearer than steam unless the fuel cost is abnormally high.

If the cost of hydraulic development can be kept below $100 per HP, water power can nearly always drive steam power out of business.

With respect to the prime movers to be employed in a hydraulic development one must be governed largely by circumstances. The choice in general lies between turbines and impulse wheels, the properties of which have been fully discussed in Chapter VII. Without attempting to draw any hard and fast lines, turbines are preferable up to about 100 feet head, unless very low rotative speed is desirable, or very little power is to be developed. Above that, the impulse wheels grow more and more desirable, and at 200 feet head the whole field is practically their own. It is generally practicable and desirable to use wheels with a horizontal axis. Only in a few instances is it necessary to resort to a vertical axis, as when there is considerable danger of the tail water rising clear up to the wheels or when, as at Niagara, a very deep wheel pit is employed.

The line of operations in developing a water power subsequent to the *reconnoissance* has already been indicated. After the more general considerations have been determined, comes the question of utilization.

It may seem needless to suggest that the first thing necessary is an actually available market, but the author has more than once had imparted to him, under pledge of solemn secrecy, the location of "magnificent" water powers which could be developed for a mere song, located a hundred miles from nowhere—out of effective range even of electrical transmission.

Having a possible market, the next thing is to investigate it thoroughly. The actual amount of steam power must be

found, together with its approximate cost in large and in small units. This information ought to be extended to at least an approximate list of every engine used and the nature of its use, whether for constant or variable load, whether in use throughout the year or only at certain seasons. These more minute data are not immediately necessary, but are immensely useful later. If it is proposed to include electric lighting in the scheme an estimate of the probable demand for lights should be carefully made. A fair guess at this can be made from the number of inhabitants in the city or town supplied. Where there is competition only with gas, experience shows that the total number of lights installed is likely to be, roughly, from one-fourth to one-sixth of the population, occasionally as many as one-third, or less than one-eighth.

From the data thus obtained one can estimate the general size of the market, and hence the approximate possible demand for electrical energy. With this in mind further plans for the hydraulic development can be made. It may be that the water power is obviously too small to fill the market, if so, it should be developed completely. If not, much judgment is necessary in determining the desirable extent of the development. Probable growth must be taken into account, but it cannot safely be counted upon. If steam power is very expensive most of the engines can probably be replaced by motors. The replacement of one-half of them is, under average circumstances, a sufficiently good tentative estimate.

With this as a basis approximate estimates of the hydraulic development can be made. This should be done by a competent hydraulic engineer. If the development is easy it is well to make estimates for a liberal surplus power also. At this stage it is best to have the hydraulic and the electrical engineer work hand in hand to estimate on the delivery of the assumed amount of power. From these estimates the general outlook for returns can be reckoned.

Before actually beginning work it is advisable to make a pretty thorough preliminary canvass of the market to see what can be done immediately in the sale of power and light. With the certain and the probable consumption ascertained, the hydraulic and electrical engineers can work their plans into final shape and prepare final estimates.

All this preliminary work may at first sight seem rather unnecessarily exhaustive, but mistakes on paper are corrected more easily than any others, and the investigation is likely to save many times its cost in the final result.

Whatever is done should be done thoroughly. Poor work seldom pays anywhere, least of all in a permanent installation, and it should be conscientiously avoided.

Above all, continuity of service has a commercial value that cannot be estimated from price lists. If it anywhere pays to be extravagant, it is in taking extreme precautions against breakdowns and in facilities for quick and easy repairs in case of unavoidable accident. This applies alike to the hydraulic and the electrical work. If the first severe freshet demoralizes the hydraulic arrangements, or the plant runs short of water at the first severe drought, a damage is done that it takes long to repair in the public mind. On the other hand careful, thorough work, coupled with intelligent foresight, insures that complete reliability that is the mint mark of honest and substantial enterprises.

CHAPTER IX.

THE ORGANIZATION OF A POWER STATION.

THE first thing to be determined in planning a power station is the proper site, which should, if steam be the motive power, be settled by convenience with respect to the supply of coal and water. In using water power the position of the station should be determined in connection with the hydraulic development. The foot of the working fall is the natural site, but, particularly in mountainous regions, it may be quite unavailable on account of lack of available space, unsuitable ground for foundations, inaccessibility, or more often danger of flood. Under high heads where a pipe line is used, one has a considerable amount of freedom in determining the site, since the pipe can be extended and led around to convenient locations at moderate expense, say not more than $3 or $4 per foot. A relatively small sacrifice of head, too, may enable one to secure an admirable location.

On low heads there is far less latitude permissible, since the canal and tail race are relatively costly and a change of level is a serious matter.

If possible the power station should be placed well off the main line of flow, or with the main floor well above high water mark. The foundations must be of the best to secure safety from floods and a proper support for the moving machinery. To meet these conditions is not always easy, particularly when the available head is low, and sometimes extreme artificial precautions have to be taken against flood. Such a case is found in the Oregon City plant already mentioned, of which a sectional view is given in Fig. 189, showing the foundations, a single generator its wheels, and their appurtenances. The inner wall of the station is here the outer wall of the canal, and both walls and foundations are built very solidly of masonry and concrete. In the cut *A* and *B* are the draft tubes belonging respectively to the wheel cases *D* and *F*, which

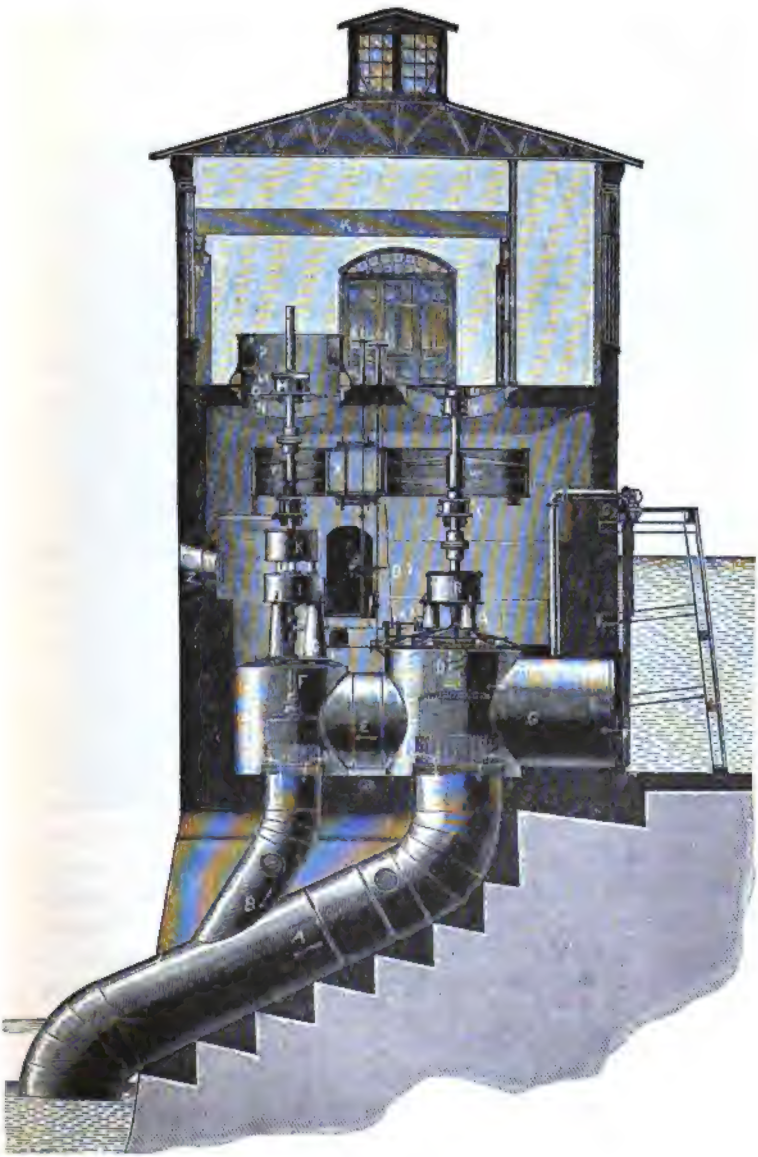


FIG. 189.

are supplied by the penstocks *C* and *E*. *F* contains the regular service turbine, a 42″ Victor wheel coupled direct to the generator at *P*. On the pedestals *G* above this wheel is a ring thrust bearing at *I* and an hydraulic thrust bearing *K*. Above this is a pulley *Y*, 6 feet in diameter, and still above this the upper bearing support, the bearings *N* and *O*, the coupling *M* and pedestals *Q*.

The wheel case *D* contains a 60″ wheel with bearings, pulley, and so forth, *R*, *S*, *W*, *T*, *U*. The function of this wheel and its attachments is to supply power at the seasons of very high water, sometimes several years apart. When the tail water backs up so far that the smaller wheel is no longer equal to the work the generator shaft is arranged to be uncoupled just above the wheel. Then the belt tightener *X* can be brought into use, the large wheel started, and the generator driven by the horizontal belt. The belt tightener is operated by hand wheels at E_2 and D_2, while similar hand wheels at C_2 and B_2 enable the wheels to be regulated by hand when desirable. The governing is normally accomplished by the automatic regulator A_2. F_2 is one of the main race gates, lifted by the mechanism at G_2. The wheelroom is lighted by water-tight heavy glass bulls eyes at *Z*, each three feet in diameter. The dynamo room is lighted by side windows and monitor roof and is fitted with a twelve ton travelling crane K_2, carried on the supporting column M_2 and N_2. The penstocks pass through the heavy cement floor of the wheelroom, J_2, with water-tight joints. The main point of interest in this station for our present purpose is not the somewhat complicated and cumbersome hydraulic plant but the structure of the wheelroom, which forms a massive permanent coffer dam securing the motive power against all direct interference by even the fiercest floods. Such a construction is somewhat inconvenient, but in some instances is almost absolutely necessary. Generally such extreme means need not be taken, although since it is usually desirable to have the dynamos on a level with the wheels, and coupled to them, a water-tight wall between the dynamo room and the wheelroom is rather common. Quite as often, however, full reliance is placed on the strength and tightness of the penstocks and wheel cases, and wheels and dynamos are placed in the same room. A plant so arranged

is cheap and simple, and where there is no considerable danger of flood is sufficiently secure. Fig. 190 shows a good typical plant of this sort, consisting of three double horizontal turbines under 50 feet head, each direct coupled to its generator.

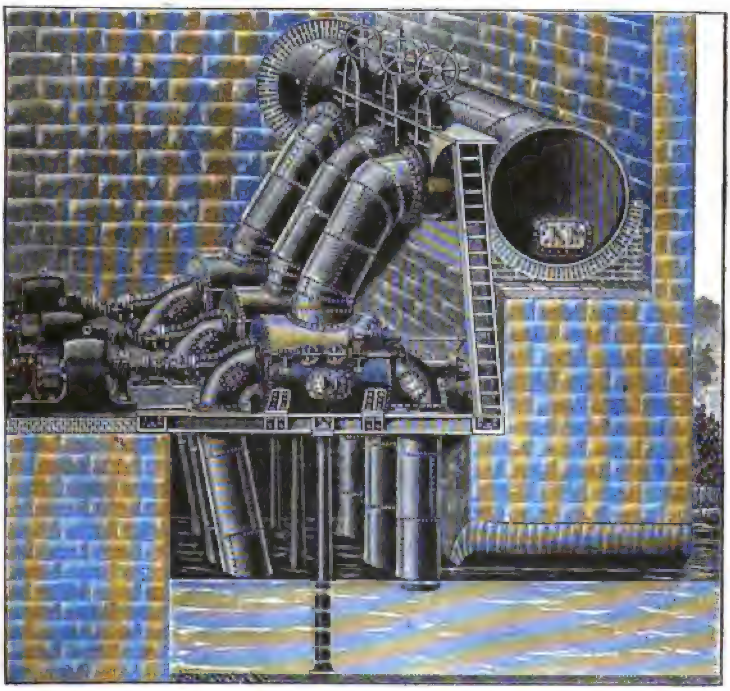


FIG. 190.

Each pair of wheels gives 560 HP at about 430 revolutions per minute. This represents construction as straightforward and simple as that of Fig. 189 was difficult and intricate.

The hydraulic conditions may drive the engineer to all sorts of expedients, but the main points are security against being drowned out, and good foundations. If the dynamos and wheels can be given direct foundations of masonry and concrete, such as the former have in Fig. 190 and the latter in Fig. 189, so much the better. If moving machinery must be carried on beams, support these beams as in Fig. 190, directly under the load, by iron pillars or masonry piers. For direct coupling it

is necessary to have foundations entirely secure from vibration. If such cannot be had one may resort successfully to a flexible coupling, but more often rope or belt driving is advisable.

The proper site having been selected the next consideration is the form of the structure itself. As a rule, whatever the nature of the power units, they are most conveniently put, in a water power plant, side by side in a single row with their shafts parallel. This placing enables the hydraulic plant to be simply and conveniently arranged, and enables the operator to

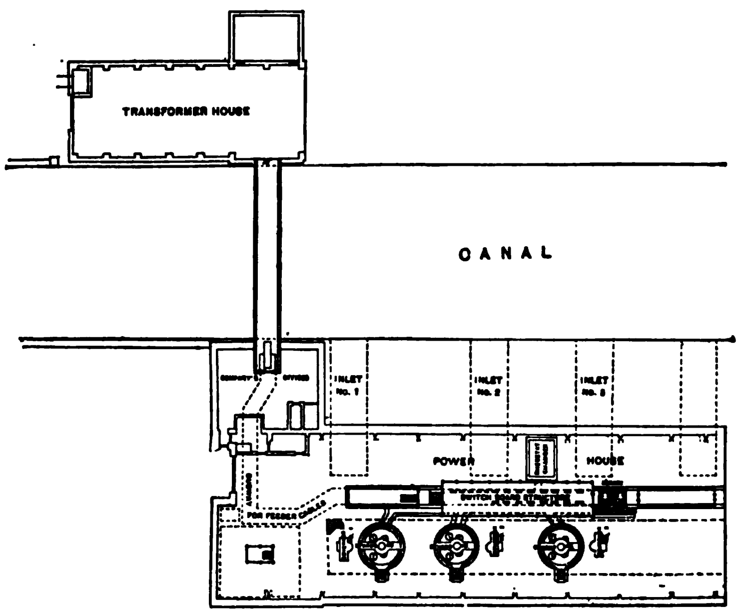


FIG. 191.

take in the whole plant at a glance and watch all the apparatus simultaneously. Fig. 191 shows a ground plan of the great Niagara station as at present constituted, well exemplifying this arrangement. In stations employing horizontal turbines such a distribution of units has even greater advantage in avoiding long and crooked penstocks. Fig. 190 forcibly suggests the difficulty of setting the generators otherwise than in a single row.

In general the building erected for a power station should be light, dry, and well ventilated. Dynamos usually run hot enough, without boxing them up in a close room. There should be plenty of space back of the row of dynamos so that if machinery has to be moved there will be ample room. On the other hand the row of dynamos should be fairly compact, as a needless amount of scattering of the machines makes them hard to look after. In very many cases one story in height is quite sufficient, and in all cases it is preferable to more, so far as working apparatus is concerned. Sometimes a second story can be well utilized for store rooms, transformer room, and quarters for the operating force, but as a rule a single story allows more complete accessibility—one of the most important features in station design. As land is seldom dear around a station for power transmission ample floor space is easily obtained, except in occasional cramped localities. A brick structure with iron roof is perhaps the most satisfactory kind of station, although for small work a frame building often answers the purpose. Window space should be large and arranged so as to avoid leaving dark corners around the apparatus. There should be, too, ample door space to facilitate replacing apparatus—nothing is more annoying than to be short of elbow room when moving heavy machinery.

For the same reason a good permanent road should be built to the power station if one is not already in existence. In mountainous regions this is sometimes impracticable, but money spent in improving the road is better invested than when put into special sectionalized apparatus. It is quite possible so to sectionalize a generator of several hundred KW that the parts can all be carried on mule back, but the expense is considerably increased, and the great advantage of having a standard type of apparatus has to be abandoned. Hence, unless the cost of improving the road to admit of transporting ordinary apparatus is decidedly greater than the difference in cost between regular and sectionalized machinery, the former procedure is advisable. Of course when it comes to a question of long mountain trails, sectionalized machinery has to be employed. The armature of a polyphase machine for use with transformers can very easily be sectionalized, but if for high voltage or of very large size it is better to send in core

plates and other material in bundles and wind the armature on the spot.

Having determined the general location and nature of the power station, one may take up further arrangements as follows:

I. Motive Power.

II. Dynamos.

III. Transformers.

IV. Accessories.

The fundamental question is the proper size and character of power units. In direct coupled work prime mover and generator must be considered together. In steam driven stations for power transmission the boiler plant may be determined by itself, but dynamos and engines should be taken up conjointly.

There is at present rather too strong a general inclination to use direct coupled units at any cost. Direct driving is beautifully simple and efficient when conditions are favorable, but belt and rope driving gives singularly little trouble, and when well engineered wastes very little energy—not over 3 to 5 per cent. for a single direct drive, which can almost invariably be used. It is very easy to lose far more than this in using a dynamo designed for a speed unsuited for its output, or wheels working under disadvantageous conditions. Cases of such misfit combinations are not uncommon, and while the workmanship and results are often good the engineering is faulty. A very characteristic example is shown in Fig. 192, from the power plant of a synchronous single phase transmission for mining purposes. The generator selected was a 120 KW Westinghouse machine of standard form and excellently adapted for its purpose. Its speed was 860 revolutions per minute, and to obtain this from a working head of 340 feet a battery of four 21 inch Pelton wheels was required. Now the Pelton wheel under favorable conditions is unexcelled as a prime mover in convenience and efficiency, but these conditions were distinctly unfavorable. The same work could have been done by a single wheel four or five feet in diameter at not over one-third the initial expense for wheels and fittings, and at enough higher efficiency to more than compensate for the slight loss of energy in a simple belt drive. In this case wheel

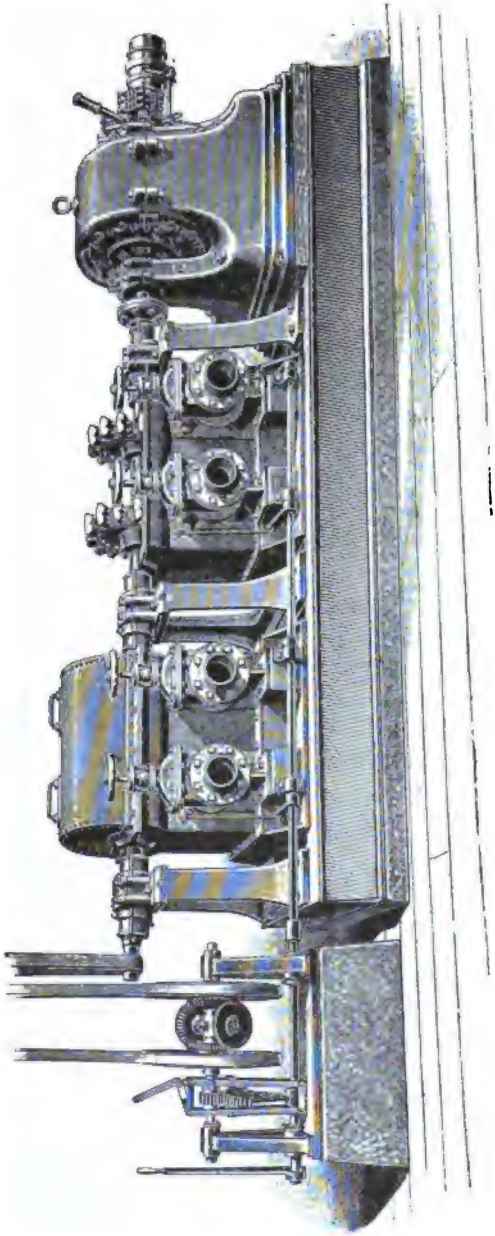


FIG. 192.

efficiency was sacrificed to the speed of the generator. An error quite as common is to sacrifice generator efficiency to the speed of the prime mover.

The most flagrant case of this kind that has come to the author's notice was a polyphase machine of less than a hundred KW output direct coupled to a vertical shaft turbine at 20 revolutions per minute. This was of course a low frequency machine, but an instance nearly as bad may be found in the case of a 75 KW alternator for 15,000 alternations per minute direct coupled to an engine at a little less than 100 revolutions per minute. These are extreme examples, of course, such machines costing several times more than normal generators of the same capacity and having probably fully 10 per cent. less efficiency. It is, however, not rare to find costly direct coupled units which gain no efficiency over belted combinations, have little to recommend them save appearance, and pay dearly for that.

The best way to avoid such mistakes is to put aside prejudice and let the makers of generators and prime movers put their heads together in consultation and work out the problem together. Both are usually anxious to do good work, and will arrive at a judicious conclusion.

Alternating work is sometimes difficult in this respect on account of the requirements of frequency, but at the present time all the large makers of hydraulic and electrical machinery have a sufficient line of patterns to meet most cases easily without involving special work to any considerable extent.

In deciding on the number of units to be employed several things must be taken into account. The number should not be so small that the temporary crippling of a single unit will interfere seriously with the work of the plant. This determines the maximum permissible size of each unit. The nearer one can come to this without involving difficulties in the way of proper speed or serious specialization, the better. It is seldom advisable to install less than three units, while in some cases a considerably larger number must be used to suit the hydraulic conditions.

To illustrate this point, suppose we are considering a transmission of 3,000 KW from a water power with 16 feet available head. One would naturally like to install three 1,000 KW

generators or four of 750 KW. But trouble is encountered at once in the wheels. The 1,000 KW machine should have say 1,500 HP available at the wheel, and the 750 KW about 1,100. Even assuming at once the use of double turbines the highest available speed for an output of 1,500 HP would be about 65 to 70 revolutions per minute, too low for advantageous direct coupling at any ordinary frequency; 1,100 HP can be obtained at a speed perhaps 10 revolutions per minute higher—not enough to be of much service. It is a choice between evils at best, either generators of speed so low as to be both expensive and difficult to get up to normal efficiency, or belting, when one would much prefer to couple direct. At lower heads, say 12 feet, one would be driven from direct connection; at 30 to 40 feet head it would be comparatively easy. In the case in hand we are near the dividing line, and it would require very close figuring to get at the real facts, figuring which would have to be guided by local conditions. The chances are that rope driven generators of perhaps 750 KW would give the best combination of efficiency and cost. Each case of this kind has to be worked out on its merits. Since the dynamos cost far more than water wheels for the same capacity, if there is any specializing to be done it is cheaper to do it at the wheels. If, however, it proves convenient to change the dynamo speed a trifle, most generators can be varied 10 per cent. either way without encountering any difficulties.

Now and then it becomes necessary to plan for vertical wheel shafts. This, unhappily, is apt to occur at very low heads, and leads to immediate difficulty. Direct coupling is usually impracticable since the speed is very low, double wheels being out of the question, and even if the dynamo could be economically built the support of the revolving element would be very troublesome. The usual arrangement is to use bevel gears, and this is generally the only practicable course. At high heads, when the speed is favorable for direct coupling, an hydraulic step can generally be relied on to carry the necessary weight.

It is desirable in any case to operate each dynamo by its own special wheels, to avoid complication. Hence the considerations which determine the number of dynamos also define the number of wheels. It is very seldom expedient to

use more than a single pair of wheels for driving a single generator, on account of difficulties in alignment and regulation and consequent tendency to work inharmoniously. This tendency is stronger in impulse wheels than in turbines on

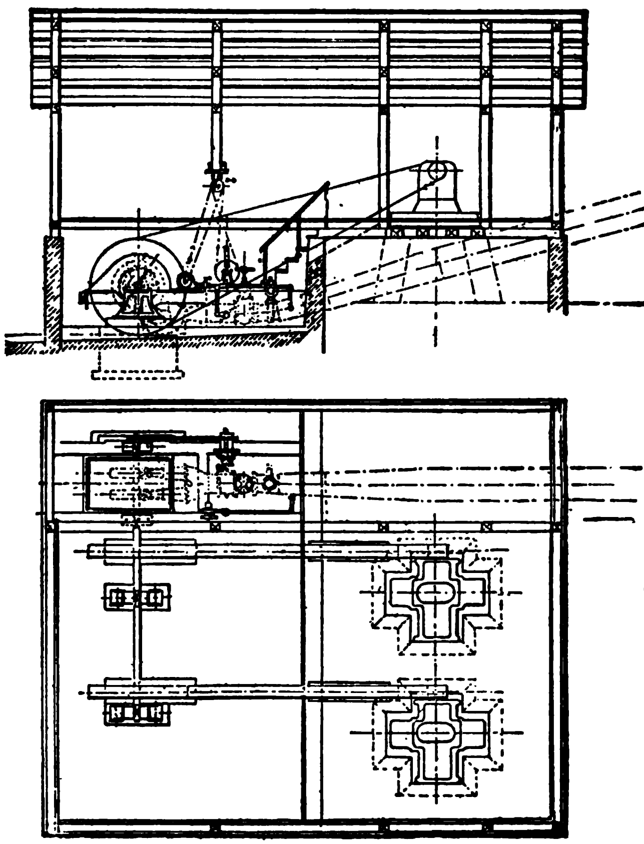


FIG. 193.

account of the very small volume of water generally employed, and consequent hypersensitiveness to small changes in the amount, pressure, and direction of the stream. So, usually, a single wheel or pair of wheels, equal to the task of handling a single generator, may be taken as the hydraulic unit.

For simplicity and economy one should keep down the

number of generators to the limit already imposed, except as special cases may call for an increase. If the plant is to feed several transmission lines it is sometimes best to assign separate dynamos to each line for one purpose or another, and this may make it necessary to increase the total number. The requisite security from accident can be in such cases obtained by one or two spare units, or by shifting a generator from a lightly loaded line to a heavily loaded one. In point of fact the modern generator is a wonderfully reliable machine, and it is not unusual to find a machine that has run day and night, save for a few hours in the week, for many months without any reserve behind it. The author saw recently a small incandescent machine which had run some hours per day in an isolated plant for fourteen consecutive years without a failure of any kind. During that time the armature had been out of its bearings but once, to have the commutator turned down.

In steam driven plants, as in water power works, the most convenient arrangement of generators is generally side by side in a single line. So placed they are easy to take care of, and the spare room is more available than when it is irregularly disposed. In case water wheels are the prime movers a water-tight bulkhead should be placed between them and the dynamos, so that leaks or overflows will be confined to the wheel pit, where they can do no harm. Through this bulkhead the shafts should pass if the units are directly coupled. In case of a belt or rope drive it is frequently convenient to place wheels and dynamos on different levels, thus obtaining similar security. Fig. 193 shows a well-arranged small plant of this sort, driven by a pair of Pelton wheels. The plant is so small that both dynamos can be conveniently driven by pulleys on a very short extension of the wheel shaft.

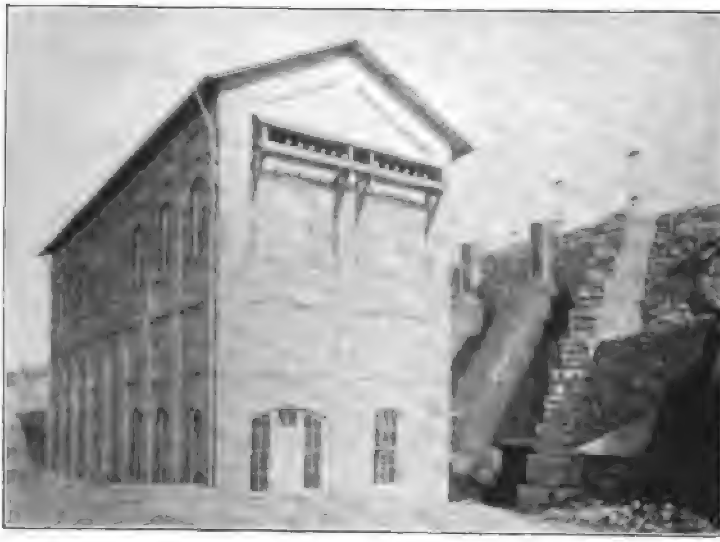
In a larger plant each wheel unit would drive a single dynamo, and the receiver and wheels with their fittings would occupy one half of the station while the dynamos would be placed in the other half, following the same general plan shown in Fig. 193. The main point is to get good foundations for the dynamos while keeping them out of reach of stray water.

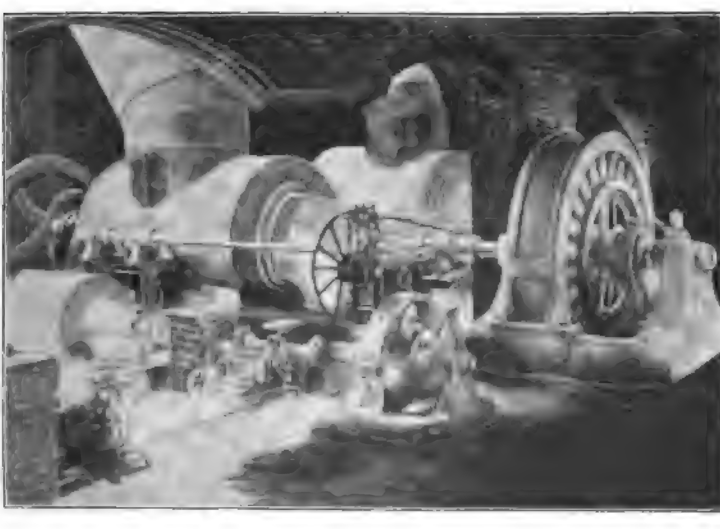
In an alternating station it is advisable to drive the exciters from special prime movers, so that a change of speed, even momentary, in the main machine may not change the exciter

voltage and thus make a bad matter worse. This is particularly necessary in water power plants, where the governing is apt to be none too close or prompt. It is a good thing also to have plenty of reserve capacity in the exciters, so as never to be caught with insufficient exciting power even in case of accident to one exciter.

Both wheels and dynamos should be thoroughly accessible, and wheel and dynamo rooms must be well lighted, naturally and artificially. A dark and slippery wheel pit, without sufficient space around the wheels, is sure to prove a source of annoyance and sometimes of serious delays. It should be possible to get at every wheel and its fittings and to work around them freely when all the other wheels are in full use. Sometimes it is useful to separate wheels by bulkheads, preferably movable, and there should always be floor space enough to stand and work on without putting up temporary stagings and loose boards. There should always be electric lights ready for use around all the working machinery, arc lamps or incandescents as may be most convenient, but plenty of them. Around the wheels it may sometimes be necessary to use incandescents in marine globes to protect them from the water, and waterproof flexible cable for the movable lights.

As an example of good practice in a plant for heavy power transmission, operated by turbines under a moderate head, the Folsom, Cal., installation shown in Plate IV. is worth studying. Fig. 1 shows the general character of the power house and its relation to the forebay, penstocks, and tail race. The forebay itself is double, being divided lengthwise by a wall, on each side of which are the gates and penstocks for two double turbines. The tail races are four masonry arches under the power house, uniting then into a single channel. The tubular steel penstocks are 8 feet in diameter, and the relief pipes above them, 4 feet in diameter. The gates are handled by hydraulic cylinders, like the head gates at the dam. It will be observed that the wheel pit is not in the power house, but in the clear space between the rear wall of the power house and the end wall of the forebay, which like the other masonry work in this plant is of granite blocks. The power house itself is a spacious two-story brick structure





on granite foundations. The lower floor is the dynamo room while the upper floor contains the transformer room, storage space, and so forth, together with the high tension switchboard, the lines from which are shown running out from the end of the building. The wheels are 30″ double horizontal turbines of the McCormick type, giving about 1,250 HP per pair at 300 revolutions per minute under the available normal head of 55 feet. There are, besides, two small single horizontal wheels for driving the exciters. Each of the main wheel units carries on its shaft a 15,000 lb. flywheel to steady its operation under varying loads.

The arrangement of the wheels and generators is admirably shown in Fig. 2, Plate IV., from a photograph taken during the process of construction.

This gives a view of one complete unit: generator, coupling, governor, turbines and flywheel, and includes also an exciter and its wheel, not yet aligned and coupled. Four such main units and the two exciters, all placed side by side in a single row, make up the plant.

The generators are three-phase machines, of 750 KW capacity, at 60 ~. Each has 24 poles, runs at 300 revolutions per minute, and weighs about 30 tons. They are of very low inductance, with polyodontal bar-wound armatures designed to give normally 800 volts between lines, and to produce a very close approximation to a true sinusoidal wave form. They are normally intended to run in parallel, although there is actually a complete circuit per machine available when wanted. The wheels were originally installed with Faesch-Piccard governors, which functioned fairly well but were not strong enough for the heavy service, and are now being replaced.

When the heavy apparatus was all in place and connected, the arched spaces shown in Fig. 2 were walled up except for shaft holes, and the wheel pit permanently separated from the dynamo room. From the dynamos the current is taken to the low tension switchboard facing the row of generators. Thence it passes to the transformer room on the second floor of the station. Here is a bank of twelve raising transformers of the air blast substation type largely used in the practice of the General Electric Company. These raise the working pressure to 11,000 volts. At this potential the current passes to the

high tension switchboard and thence to the line. A second switchboard in the transformer room serves to distribute the low tension current received from the dynamos.

The line consists of four complete three-phase circuits each of No. o B. & S. wire. There are two independent pole lines running side by side a few rods apart, constructed of redwood poles 40 feet long. Each pole line carries two circuits symmetrically arranged on two cross arms, one circuit being on each side of the pole, the wires arranged so as to form an equilateral triangle, with an angle downward. One of the pole lines carries an extra cross arm a few feet below the main circuits, to accommodate the telephone circuit. All wires are transposed at frequent intervals to lessen induction. The pole line is on the southern side of the American River and follows in the main the county roads clear into Sacramento, the two lines being on opposite sides of the road. The route thus followed is a trifle longer than the actual linear distance, but the gain in accessibility more than counterbalances the extra mile or so of line. The high tension line is carried along the river through the northern edge of the city fairly into the district of load, and is then terminated in a handsome brick substation containing the transformer and dynamo rooms and the offices of the company. The distribution system is mixed in character owing to the operation of the existing railway and lighting loads. The dynamo room contains three 300 HP three-phase synchronous motors coupled to a line shaft, from which are driven the railway generators and the arc machines for the city and commercial circuits. These motors receive current at 500 volts from the reducing transformers in the second story.

The main distribution circuit is a three-phase four-wire circuit worked at 125 volts between the active wires and the neutral. This gives an admirable network for lighting and motor work, very economical of copper, easy to wire and to operate. All the transformers in the substation are arranged for a secondary voltage of 125, 250, or 500 as may be desired, so as to be ready for any kind of service.

This plant first went into operation in July, 1895, and has since then been in continuous service day and night. No serious trouble has been encountered, the high voltage line has

performed admirably, and there has been no difficulty due to inductance, lack of balance, resonance, or any of the other things that used to be feared in connection with long distance polyphase work. Furthermore the plant is a success financially as well as electrically. Apart from Niagara, which even now is only beginning long distance work, it is the most striking and typical transmission plant yet installed in this country.

Another fine example of three-phase work, of especial interest as being the longest power transmission yet attempted anywhere, is the plant utilized at Fresno, Cal. Fresno is a flourishing city of 15,000 inhabitants at the head of the magnificent San Joaquin valley in central California. Like other Californian cities it has been hampered in its development by the very high cost of coal—$8 to $10 per ton in carload lots, and some of its active citizens cast about for an available water power to develop electrically. Such an one was found on the north fork of the San Joaquin River very nearly 35 miles from the city. At a point where this stream flows through a narrow cañon it was diverted, and the stream was carried in a series of flumes and canals winding along the hillsides for seven miles to a point where it could be dropped back into the river bed 1,600 feet below.

At this point an emergency reservoir was formed in a natural basin which by an expenditure of less than $3,000 was developed into a pond capable of holding enough reserve water for several days' run at full load.

The minimum flow of the stream is 3,000 cubic feet per minute, capable of giving between 6,000 and 7,000 HP off the shafts of the water wheels when fully utilized. In the initial plant only a small portion of this power is employed. From the head works at the reservoir a pipe line is taken down the hillside to the power house. The pipe is 4,100 feet long. At the upper end for 400 feet a 24 inch riveted steel pipe is used, then lap-welded steel pipe is employed diminishing in diameter and increasing in thickness toward the lower end, where it is 18 inches in diameter, of five-eighths inch mild steel, and terminating in a tubular receiver 30 inches in diameter, of three-fourths inch steel. The vertical head is 1,410 feet. This corresponds to a pressure of 613 lbs. per square inch, while the emergent jet has a spouting velocity of 300 feet per second!

To withstand and utilize this tremendous velocity unusual precautions were necessary. The main Pelton wheels, designed for 500 HP at 600 revolutions per minute, have solid steel plate centres with hard bronze buckets. Each carries on its shaft a steel flywheel weighing 3 tons and 5 feet in diameter. With their enormous peripheral speed of over 9,000 feet per minute, these have a powerful steadying effect on the speed of the generators. There are three of these wheels, each directly coupled to a 350 KW General Electric three-phase generator, giving 700 volts at 60~. There are also two 20 HP Pelton wheels, each 20 inches in diameter, and each direct coupled to a multipolar exciter. All the wheels are controlled independently by Pelton differential governors.

On the main floor of the power house opposite the generators is the bank of raising transformers. These are six in number, of 125 KW capacity each, of the ordinary air blast type. Space is provided for three more when the load demands them.

These transformers raise the pressure to 11,200 volts between lines and from the high tension section of the switchboard the current passes to the transmission line. This consists of two complete three-phase circuits which can be worked together or independently. They are of No. 00 bare copper wire carried on special double petticoat porcelain insulators, all tested at 27,000 volts alternating pressure.

The pole line is of 35 foot squared redwood poles set 6 feet deep. Each pole carries four cross arms. Three of these at the top of the pole are for the transmission circuits. These are at present confined to the two upper cross arms, leaving space for additional circuits below. A fourth short cross arm about 4 feet below the others carries the telephone wires.

Plate V. gives a good idea of the general arrangement of the Fresno plant. Fig. 1 gives a glimpse of the storage reservoir at the upper end of the pipe line. Fig. 2 shows the situation of the power house below, which is built of native granite on a solid rock foundation, with a wooden roof. It is 75 × 30 feet in size. The wheel pit is seen running along one side of the station just outside the wall, through which pass the wheel shafts driving the dynamos inside. In the foreground appears the beginning of the transmission line.

Fig. 3 shows the interior of the power house with the dynamos and transformers in place and the switchboard at the further end of the room.

In the city of Fresno the transmission lines are taken to a substantial brick substation in the centre of the city. Here are situated the reducing transformers and accessory apparatus, including two 80-light arc dynamos direct coupled to 60 HP induction motors.

The distribution system is threefold. In the central district of the city a three-phase four-wire network is employed, supplied from three 125 KW reducing transformers, and worked at 115 volts between active wires and neutral. For the outlying residence region three 75 KW transformers supply current at 1,000 volts for use with secondary transformers. Finally, for reaching neighboring towns, three 40 KW transformers feed a 3,000 volt sub-transmission system. The operation of this plant, like that of the Folsom plant, has been highly successful from the start, and the electrical troubles that have often been feared on long lines at high voltage have been conspicuous by their absence.

Both these plants represent the best modern practice in general equipment and arrangement, and while differing conditions bring their own necessary modifications, these examples may be regarded as thoroughly typical. They have incidentally demonstrated the thorough practicability of general distribution of energy for lighting and power by polyphase currents under large commercial conditions, and at distances great enough to involve all the electrical difficulties likely to be met at the voltage employed. At present long distance plants are rather the exception, and in the natural course of events there must be developed a great number of power transmissions at quite moderate distances, under ten miles or so. Such plants as regards general organization do not possess any special peculiarities. The dynamos, however, may often be wound for exceptionally high voltage. Dynamos for use with raising transformers should be of moderate voltage, seldom over 1,000 volts unless the units are of immense size, or must furnish local power in addition to their regular function.

At moderate voltage the generators gain in cost per unit of

output, in simplicity, and in comparative immunity from accidents. They are also likely to be designed for lower armature reaction. Nevertheless, there are many cases in which generators for 4,000 to 6,000 volts may be properly employed for the sake of economy and simplicity of plant. As already indicated such generators should preferably have stationary armatures, and should have extraordinarily good insulation. When installed they should be insulated from the foundations with scrupulous care, and when direct coupled should be provided with insulating couplings. Small high-voltage machines are sometimes supported on porcelain insulators. Large generators may be carried on hardwood timbers thoroughly treated with insulating material, and bolted to the foundation cap stone; or, at higher voltages, on polished dense stone blocks set in sulphur and surrounded with oil grooves like those on a high voltage insulator, and in divers kindred ways which will suggest themselves to the constructor. It is desirable to surround such machines with an insulated platform a few inches above the floor, and to protect the leads with vulcanite tubes. It is well also to shield the terminals so that only one can be manipulated at a time when the machine is in action.

In all plants employing more than a single generator, and this means nearly all power transmission plants of every kind, the generators should be arranged to run in parallel, and in most instances should be so operated regularly. Now and then generators may advantageously be operated on separate lines, as when these lines must be run under different conditions of regulation, or when a line must be isolated for the purpose of carrying a very severe fluctuating load, but for the vast majority of plants these expedients are totally unnecessary, and only complicate the operation of the system without any material compensating advantage.

Plants operated for lighting alone can get along after a fashion by shifting load quickly from one machine to another, an operation quite familiar to most people who have been customers of such a system; but for the general distribution of lights and power this procedure is inadmissable, for it usually means stopping some or all of the motors. Moreover it is a clumsy method at best, abandoned long ago by continuous

current stations, and without any excuse for existence save villainously bad generator equipment or incompetence in the operation of the station.

All modern generators of good design are capable of running in parallel without the slightest difficulty, provided they have somewhere nearly similar magnetic characteristics and are intelligently operated.

It is inadvisable to attempt running a smooth-core and an iron-clad armature in parallel, or two machines which are very different in regulation or which give very different wave shape. but on the other hand such machines ought not to be installed together on general principles. The nearer alike the machines the better they will run in parallel.

No subject has been oftener a topic of fruitless discussion than the paralleling of alternators. As a matter of fact any two similar alternators will go into parallel and stay there with very little difficulty.

High inductance machines have been supposed to be somewhat easier to put and work in parallel than those of low inductance. They certainly can be thrown together carelessly with less likelihood of a large synchronizing current flowing between them, but with low inductance machines a little more care, or an inductance temporarily inserted between the machines, leads to the same end.

In throwing two alternators of any kind in parallel, they should be in the same phase, running at the same speed and at approximately the same voltage. The more nearly these conditions are fulfilled the less synchronizing current will flow between the machines, and hence the more smoothly will they drop together.

The ordinary arrangement of phase lamps shows the relation of both speed and phase with ample exactness. When the indicator lamp is pulsating at the rate of one period in four or five seconds, it is evident that the relative speeds of the machines are very nearly right, and it is quite easy to cut in the new machine when its phase is very nearly right. One soon gets the swing of the slow pulsations, and can catch the middle point of the interval of darkness with great accuracy.

It is obviously necessary that the speeds of the two machines should be normally alike, and that the speeds should have a

certain slight flexibility. When belt driven from the same shaft the various generators to be put in parallel must be run very accurately at the same speed, else one of the belts will constantly slip and there will be considerable synchronizing current. When properly adjusted the machines should be so closely at speed that the phase lamps will have a period of not far from half a minute. This is not a difficult matter when driving from the same shaft. In direct-coupled units, or in general those driven from independent prime movers, it is best to let one governor do the fine adjustment of speed, the others being a little more insensitive. Otherwise the governors are likely to fight among themselves and be perpetually see-sawing.

With respect to equality of voltage, the better the regulation of the generators in themselves the more necessary it is to have them closely at the same voltage when put into, or when running in, parallel. Two generators with bad inherent regulation will divide the load with approximate equality, even if put in parallel with a noticeable difference in voltage, since the machine that tends to take the heavier current will promptly have its voltage battered down and the tendency corrected—at the expense, however, of accurate regulation in the plant.

With machines of low inductance and good regulation, the voltages should be very closely the same before putting into parallel, to avoid a heavy synchronizing current, and they will then divide the load correctly with a very slight adjustment of the voltage. If the characteristics of the machines are known, as they should be, the voltages can be arranged so that they will fall together as accurately as if the added machine had been put on an artificial load before parallelizing.

If these precautions are observed no difficulty will be experienced in parallel running, and machines in stations several miles apart will work together in perfect harmony. This is sometimes necessary in large central station work, when a portion of the power is transmitted from a distance and a portion generated on the spot. It sometimes happens, too, that to obtain the amount of water power that is desired it must be taken from a group of falls.

The magnitude of the transformer units, when transformers are used, should be determined by the same considerations that apply to generators, except that questions of speed do not

have to be considered. The smallest number of transformers that it is desirable to use is that number which will permit the disuse of a single unit without inconvenience. Above this number one must be guided by convenience, but in general the fewer units the better, since transformers such as are used in large transmission work vary very little in efficiency under varying load, and hence there is no considerable gain in using small units so as to keep them fully loaded. When using large transformers the difference in efficiency between full load and half load should be no more than two or three-tenths of a per cent., and as a rule the general efficiency cannot be sensibly improved by using smaller units.

In polyphase transmission the transformer unit must be taken to include all the phases, so that this unit will usually consist of two or three allied transformers. In three-phase work the circuit can be operated either with two or three transformers, so that in a measure each transformer group contains a reserve of capacity, since if a transformer fails the remaining pair can be connected to do two-thirds of the work.

It is advisable in arranging the transformer plant to bear this in mind. A spare transformer or two is a good form of insurance. In the station raising transformers alone are concerned. These are likely to be of large capacity and high voltage. The individual transformers will very seldom be as small as 50 KW, and the voltage is sure to be from 5,000 volts upward to 10,000, 15,000, or 20,000 volts, and sometimes even more.

Such transformers should be treated with the respect that their voltage demands. It is always best to install them in a separate room or otherwise to isolate them so that they shall be accessible only to those persons directly concerned with them.

They should be very thoroughly insulated from the ground. As good a way as any is to carry them on porcelain blocks upon a floor of dry wood covered or saturated with insulating compound. A good precaution is to carry around them a floor of treated wood supported on porcelain insulators and of such width that anyone touching the transformers must have stepped upon the insulated platform. The transformers should not be crowded and the high voltage leads should be taken out in plain sight and insulated with vulcanite tubes.

Each transformer should have independent means for cutting it into and out of service. Such switches should be insulated with extraordinary care. It is best to have no exposed metal on the high tension switches, and long insulated handles, and one should locate all the high tension apparatus together on a special switchboard guarded by an insulated platform. All leads to and from this board ought to be run in as straightforward a way as possible, so that each wire can be traced without the slightest effort, and all the connections at the back of the board should be simply arranged with ample space between them. Finally, the transformers and all their connections should always be treated as dangerous in spite of all other precautions.

These directions may seem at first sight over-cautious, but it must be remembered, first, that the raising transformers and their connections carry the highest voltage that conditions permit, and second, that such voltage is highly formidable; 10,000 volts even, now to be regarded as an ordinary voltage for transmission work, has little respect for anything but extraordinary insulation and plenty of it, while at higher voltages the striking distance rapidly increases. The static effects of these pressures are prodigious, and neighboring wires, even if disconnected, must be handled with caution.

In small stations it may be convenient to install all apparatus in a single room, but even then the transformer plant should be carefully guarded.

In most cases large transformers are artificially cooled and must be installed with that in view, but air blasts or circulating pumps do not involve any special considerations except that spare parts must be at hand in case of accident.

It should of course be understood that transformers in power transmission work can be, and very often are, worked in parallel with the greatest facility. Transformers to be so used must have closely similar magnetic characteristics, and particularly must regulate alike under varying loads. They must also have independent fuses or other safety devices, so that each can take care of itself. In all cases it is highly desirable to have one or more spare transformers ready to be cut in at a moment's notice anywhere that may be necessary.

Where transportation is difficult the installation of trans-

formers is rather a serious problem. Generally speaking it is best to sectionalize the coils, each section being independent and fully insulated. The core plates can then be taken in in bundles and the transformers built up on the spot, with whatever additional insulation may be necessary. Of course means must be at hand for the final testing, including a small testing transformer to obtain the necessary voltage.

The most important accessories of a plant pertain to the switchboard. This must be built with particular care in high voltage work. Its location, as a general thing, should be on the floor of the dynamo room, except as the high tension section may be placed in the transformer room near the apparatus which it serves. The general rule should be so to place the switchboard with respect to its apparatus that it shall be very accessible, and where both may be easily watched at once by the attendants. Sometimes in very large stations the switchboard is isolated and in constant charge of a special attendant, but the practice is not to be generally recommended.

As to materials, marble is by far the best yet employed in point of beauty and fine insulating properties. Slate has often been used, but is rather unreliable both as an insulator and mechanically. The switches may either be on individual bases and bolted to the switchboard or mounted directly upon it without separate bases. For large permanent work the latter course is preferable. It is now quite customary to mount the equipment for each individual generator in a single complete panel and, except for very large work, this is exceedingly convenient.

High voltage switches require special construction. When the generator gives from 3,000 to 5,000 volts, or when these or higher voltages are derived from transformers, the danger of arcing across at the switch is quite serious and the switch gaps must be corresponding wide. They may often be advantageously reinforced by insulating barriers. In a plant using raising transformers the switches should be, so far as possible, on the low voltage side, so that need for opening a switch under pressure on the high voltage side may be avoided.

Modern generators with small armature reaction and low inductance produce ferocious arcing when the circuit is opened

in case of a short circuit, for the voltage does not drop much. Hence all safety devices must be planned accordingly. Plenty of room is the main point. Magnetic cutouts are generally preferable to fuses, but when the latter are used they must be thoroughly protected against the maintenance of an arc. A few close-fitting large asbestos paper washers strung along a fuse will break almost any kind of an arc, but the fuses in different lines should be far enough apart to prevent the arc cutting over from line to line instead of trying to follow the break. In transformer plants the safety devices are usually put only on the low voltage side of the circuit, and as a rule the high tension lines are let severely alone when carrying current.

Money spent in accurate switchboard and testing instruments is well invested. Ammeters and voltmeters should be of the best quality and accurately adjusted when in place on the switchboard. For station use the instruments with very large dials are to be recommended for their easy visibility. One should not have to smell of an instrument to discover the reading. The voltage on high tension lines is most conveniently measured by transforming down, but in large stations it is desirable to have direct-reading testing instruments. Up to about 3,000 volts reliable voltmeters can easily be obtained, but much beyond that one must use electrostatic instruments or rely solely on transformation.

The main circuits should be equipped with integrating wattmeters as a final check on the station output. This is particularly valuable in alternating stations since, in connection with the other instruments, it gives the power factor of the plant, which should be closely watched.

A much neglected but highly desirable accessory in high voltage work is some means of measuring the line insulation under the stress of the normal voltage.

In the way of mechanical fittings, the first place should be given to a travelling crane, capacious enough to move everything which is likely to need moving about the plant. Not only is it exceedingly useful in installation but it may be needed for repairs, and in such case may save much valuable time.

It is very important to have at least one man about the

plant who is a good practical mechanic, and to provide a workroom and tool equipment enough to enable small repairs to be made on the spot. In most cases material and tools for minor electrical repairs are necessary and they are always desirable, for they make it possible to forestall further repairs and often will tide over an emergency, even if outside help has finally to be called in. The more isolated the station the more necessary it is to make such provisions, and the more spare parts must be at hand. Of line material there should always be plenty in stock to repair breaks, and this stock should never be allowed to get low.

Finally, as regards attendance, incompetent men are dear at any price. It pays to employ skilled men and to make it worth their while to settle down to permanent work. They are valuable all the time, and can be depended upon in an emergency when less competent ones would fail. In this as in other things avoid the fault stigmatized in the vernacular as "saving at the tap and spilling at the bung-hole."

CHAPTER X.

THE LINE.

The line is a very important part of a power transmission system, for on its integrity depends the continuity of service without which even the most perfect apparatus is commercially useless. In most cases the customer who uses electrical power neither knows the efficiency of his motor nor cares much about it, so long as the machine goes steadily along without the annoyance and expense of frequent repairs. But if the service frequently fails, suspending the operation of all his machinery while repairs are being executed, the electric motor, so far as he is concerned, is a commercial failure, and a nuisance to boot, and no representations of cheap power can be of much avail when a single stoppage may cause more loss than could be recompensed by free power for a month.

Modern dynamos and motors of almost every class are reasonably efficient and reliable, so that as a rule the line is the weakest portion of the system. More particularly is this the case when the distance of transmission is great and many miles of line must be guarded, inspected, and kept in perfect working order. In such long lines not only is the actual labor of maintenance great but the principal engineering difficulties will there be encountered. With apparatus of the character even now available, the future of electrical power transmission depends in very large measure on the development that takes place in the construction, insulation, and maintenance of the line, together with the solution of certain electrical problems that arise as the line grows longer. It is therefore important to go into the matter very carefully, as regards not only the general arrangements and the electrical details of the work, but with respect to methods of construction.

We may then with advantage divide our consideration of the line into three heads. First, the line in its general relations to the plant, considering it merely as a conductor. Second,

the line as a special problem in engineering. Third, the line as a mechanical structure. Of these heads the first has to do with such questions as the proper proportioning of the line as a part of the system, its function as a distributing conductor, and its bearing on the general efficiency of the plant of which it is a part. Next come up for examination the electrical difficulties that appear in the line, and finally the materials of construction and the methods of applying them.

One of the first questions that arises in designing a plant for the transmission of power is the character and dimensions of the conducting system in their relation to the rest of the plant. Efficiency is generally the first thing thought of—cost comes as a gloomy afterthought; and between these two good service is only too frequently neglected. In taking up a transmission problem the layman's first query generally is, "How much power will be lost in the line?" and when the engineer answers, "As much or as little as you please," the subject of line design is opened up in its broadest aspect.

Whenever an electrical current traverses a conductor there is a necessary loss of energy due to the fact that all substances have an electrical resistance which has to be overcome. The energy so lost is substantially all transformed into heat, which goes to raising the temperature of the conductor, and indirectly that of surrounding bodies. The facts in the case are put in their clearest and most compact form by Ohm's law, $C = \frac{E}{R}$. This states that the current is numerically equal to the electromotive force between the points where the current flows, divided by the resistance. Hence, this E. M. F. equals the current multiplied by the resistance between these points.

$$E = CR.$$

This tells us at once the loss in E. M. F. between the ends of any line provided we know the current flowing and the resistance of the line. And inasmuch as the energy transmitted by the same current varies directly with the working E. M. F., a comparison of the loss in volts determined as above, with the initial E. M. F. applied to the circuit, shows the percentage of energy lost in the line. Obviously its

absolute amount in watts is equal to the E. M. F. lost, multiplied by the current, *i. e.*, $C E$, or from the last equation, $C^2 R$, if we prefer to reckon in terms of the resistance.

Ohm's law is the basis of all computations regarding the line, and lies behind all the formulæ used for this purpose. The most obvious way of applying it would be to find the resistance of the whole line corresponding to any required current and loss of volts, and then to look up in a wire table the wire which when taken of the required length would give this resistance. As a matter of convenience in computation a large number of formulæ have been devised, which include the distance; loss, expressed either in volts or percentage lost; energy transmitted, in watts, horse-power and the like; and various other factors, which may be convenient for particular applications. Some of the formulæ give the total weight of copper required, and others the area of the conductor expressed in various ways.

Of these formulæ, all modified from Ohm's law to suit various conditions, the most generally convenient are those which give the area of the required conductors in "circular mils" (*i. e.*, circles one one-thousandth of an inch in diameter), a barbarous unit familiar in all tables of wire sizes, which unfortunately has obtained too firm a hold on electrical practice to be readily shaken off.

Of these "circular mil" formulæ one is subjoined which has been found by the author to be most convenient on account of its simplicity. It is derived from Ohm's law as follows: $R = \frac{C}{E}$. Now for any length of wire $R =$

$$\frac{\text{Total length in ft.} \times \text{resistance of 1 ft. wire 1 mil in section}}{\text{Area in circular mils.}}$$

Taking the total length of wire as twice the distance of transmission in feet, since this distance is particularly in mind, and noting that the resistance of one "mil-foot" of commercial copper wire is quite nearly 11 ohms, we have

$$R = \frac{2\,D \times 11}{c.\ m.}$$

Substituting this value of R in the expression of Ohm's law just noted, and solving for the value of $c.\ m.$ we have,

$$c.\ m. = \frac{2\ D \times 11 \times C}{E}.$$

In this expression E is the number of volts lost, and 11 is taken as the "mil-foot" constant, since it is large enough to take account of variations in diameter of wire, bad joints, flaws, and the like. The theoretical value is nearer 10.8, but experience has shown the wisdom of making the above allowance.

Having found in any case the area of the required wire in circular mils, its size and weight per thousand feet can be looked up in any wire table.

Since it chances that a wire of 1,000 *c. m.* weighs very nearly 3 lbs. per thousand feet, we can obtain a very simple formula giving directly the weight in pounds of wire per thousand feet. Taking D in thousands of feet, and expressing this fact by writing it D_m, we have:

$$W_m = \frac{2\ D_m \times 33 \times C}{E};$$

or for the total weight of wire

$$W = \frac{4\ D^2_m \times 33 \times C}{E}.$$

As a matter of convenience, the following table is inserted, giving, for the sizes of wire most used in power transmission work, the area in circular mils, the diameter, resistance per thousand feet, and weight per thousand feet, both bare and with insulation of the so-called "weather-proof" grade, which is well adapted for ordinary line work. Diameters are here given to the nearest mil, areas to the nearest 10 *c. m.*, and

Circular Mils.	Gauge No. B. & S.	Diameter in Mils.	Resistance in ohms per M feet.	Wt. per M feet Bare.	Wt. per M ft. We'th'r proof.
211,600	0000	460	.04904	640	725
167,800	000	410	.06184	508	580
133,100	00	365	.07797	403	480
105,600	0	325	.09827	320	375
83,690	1	289	.12398	253	307
66,370	2	258	.15633	201	245
52,630	3	229	.19714	159	195
41,740	4	204	.24858	126	147
33,100	5	182	.31346	100	121
26,250	6	162	.39528	79	99

weights to the nearest pound. The table is not continued beyond the size given, because anything larger than No. .0000 is exceedingly troublesome to string, and when called for is better replaced with two smaller wires. On the other hand, wire smaller than No. 6 is seldom indicated by the conditions, and produces a mechanically weak line.

The above formulæ and table give sufficient data for computing the general character of a transmission line provided the loss in volts is determined. In actually working out the amount of copper needed in any given case, certain details require to be taken into account which will be discussed later.

A glance at the formula shows that the voltage employed is the determining factor in the cost of the lines. For a fixed percentage of loss doubling the working voltage will evidently divide the amount of copper required by four, since the current for a given amount of energy will be reduced by one-half, while the volts lost will be doubled.

So in general the amount of copper for transmitting a given amount of energy a given distance at a fixed efficiency will vary inversely as the square of the voltage.

If the distance of transmission is doubled, the area of the conductor will evidently have to be doubled also; consequently, since the length is doubled, the weight of copper will be increased four times. That is, for the same energy transmitted at the same per cent. efficiency and voltage, the weight of copper will increase directly as the square of the distance. The advantage and, indeed, necessity of employing high voltages for transmissions over any considerable distance is obvious. In fact, it will be seen that by increasing the voltage in direct proportion to the distance, the weight of copper required will be made a constant quantity independent of the distance.

If one were free to go on increasing the voltage indefinitely without enormously enhancing the electrical difficulties, power transmission would be a simple task, but unfortunately such is not the case. With very high voltages we meet difficulties both in establishing and maintaining the insulation of the line, and in utilizing the power after it is successfully transmitted. The specific character of these limitations will be discussed later, but enough has been said to render it evident that in

establishing a power transmission system, both the working voltage and the volts lost in the line must be determined with great judgment.

In the matter of economy in the line, high voltage is desirable—first, last and always. In systems where the voltage undergoes no transformation its magnitude is somewhat arbitrarily fixed by the practicable voltage which can be employed in the various translating devices, motors, lamps and the like. For example, in a system at constant potential wherein incandescent lamps are an important item, 125 volts or 250 volts worked on the three-wire system would be the highest pressure advisable for the receiving system in the present state of the art. For a direct-current-motor system the corresponding figure would be 500 to 600 volts or 1,000 to 1,200 three-wire. Similar limitations indicated elsewhere will hold for other classes of apparatus.

When there is a transformation of voltage in the system, whether direct or alternating current, so that the line voltage is not fixed by that of the translating devices, it is advisable to raise the voltage of transmission as high as the existing state of the art permits. It must be borne in mind, however, that this general rule is subject to modification by circumstances. It would be bad economy, for instance, to use very high pressures and costly insulation for a transmission of moderate length and trifling magnitude. Such practice would result in sending perhaps 100 KW over a line or through a conduit which could as easily serve for ten times the power without great additional cost for copper. It is well, however, not to stop at half-way measures, but if transforming devices are to be used at all, to go boldly to the highest voltage which experience has shown to be safe on the line, or in the generators, if only reducing transformers are used.

For example, in most cases of alternating current work, 1,000 volts is of doubtful utility; if the line voltage has to be reduced at all it is better to get the advantage of 2,000 to 5,000 volts on the line; if raising transformers are employed the latter figure might as well be increased to 10,000, unless climatic or other special conditions are unfavorable.

It will be seen that quite aside from engineering details, divers really commercial factors must enter into any final

decision regarding the voltage to be used. And these commercial factors are the final arbiters as to the working voltage, and even more completely as to the proportion of energy which it is desirable to lose in the line. Power transmission systems are installed to earn money, not to establish engineering theses.

It is evident, to start with, that whatever the voltage, high efficiency of the line and low first cost are in a measure mutually exclusive. The former means large conductors, the latter small ones; the former delivers a large percentage of salable energy, with a high charge for interest on line investment; the latter a smaller amount of energy, with a lessened interest account against it. At first sight it would seem easy to establish a relation between the cost of energy lost on the line and the investment in copper which would be required to save it, so that one could comfortably figure out the conditions of maximum economy.

In 1881 Lord Kelvin, then Sir William Thomson, attacked the problem and propounded a law, known often by his name, which put the general principles of the matter in a very clear light, but which indirectly has been responsible for not a little downright bad engineering.

He stated, in effect, that the most economical area of conductor will be that for which the annual interest charge equals the annual cost of energy lost in it.

While it is true that for a given current and line Kelvin's law correctly indicates the condition of minimum cost in transmitting said current, this law can only mislead when applied to many concrete cases of power transmission, for it omits most of the practical considerations. It involves neither the absolute value of the working voltage nor the distance of transmission, and for long transmissions at moderate voltage often gives absurd values for the energy lost. Indeed, as it deals directly only with the most economical condition for *transmitting* energy, it quite neglects the amount of energy delivered. In fact, one may apply Kelvin's law rigidly to a concrete and not impossible case, and find that no energy to speak of will be obtained at the end of the line.

In other words, Kelvin's law, while a correct solution of a particular problem, is in its orginal form totally inapplicable to most power transmission work.

Various investigators, notably Forbes and Kapp, have made careful and praiseworthy attempts so to modify Kelvin's law as to take account of all the facts; indeed, nearly every writer on power transmission has had a shy at the problem.

Perhaps the commonest attempt at improvement is to follow the general line of the original law, but to equate the interest charge on copper to the annual *value* of the power lost; in other words, to proportion the line by increasing the copper until the annual net value of a horse power saved in the line would be balanced by the interest charge on the copper required to save it. This proposition sounds specious enough at first hearing. Practically, it produces a line of far greater first cost than is usually justified. It is evident that the possession of a little extra power thus saved brings no profit unless it can be sold, and in very few cases is a plant worked close enough to its maximum capacity during the earlier years of its existence to render a trifling increase in output of any commercial value, especially in the case of transmission from water power. When the plant is worked at a very high cost for power, or soon reaches its full capacity, a few horse power saved in the line will be valuable; but far oftener, particularly in water-power plants, it would be cheaper to let the additional copper wait until the necessity for it actually arises. Furthermore, it evidently does not pay to so increase the line investment that the last increment of efficiency will bring no profit.

As an example, let us suppose the case of a 1,000 HP transmission so constituted that the line copper costs $10,000 with 10 per cent. loss of energy in the line, and suppose in addition that the net value of 1 HP at the receiving end is $50 per annum. It is evident that by decreasing the loss in the line to 2½ per cent. there would be available 75 additional HP worth $3,750 per annum. The cost of this addition to the line would be $30,000, on which interest at 6 per cent. would be $1,800. So long as the plant is not worked up to 90 per cent. of its maximum capacity of 1,000 HP there will be a steady charge of $1,800 plus depreciation if the additional copper be installed at the start. A few months' loss at this rate would more than cover the labor of reinforcing the line when needed, even supposing that installing the additional

copper at the start would not have involved extra labor in construction.

Various formulæ for designing the line so as to secure the minimum cost of transmission have been published, derived more or less directly from Kelvin's law and attempting to take into account all the various factors involved in line efficiency. They all contain quantities of very uncertain value, and hence are likely to give correspondingly inexact results. More than this, they are founded on two serious misconceptions.

First, they generally give the minimum cost of transmission, which is not at all the same thing as the maximum earning power on the total investment. Second, however fully they take account of existing conditions, the data on which they are founded refer to a particular epoch, and are very unreliable guides in designing a permanent plant.

A few years or even months may and often do so change the conditions as to lead to a totally different result. In the vast majority of cases it is impossible to predict with any accuracy the average load on a proposed plant, the average price to be obtained for power, or the average efficiency of the translating devices which will be used. So probable and natural a thing as competition from any cause, or adverse legislation, will totally change the conditions of economy.

For these reasons neither Kelvin's law nor any modification thereof is a safe general guide in determining the proper allowance for loss of energy in the line. Only in some specific cases is such a law conveniently applicable. Each plant has to be considered on its merits, and very various conditions are likely to determine the line loss in different cases. The commonest cases which arise are as follows, arranged in order of their frequency as occurring in American practice. Each case requires a somewhat different treatment in the matter of line loss, and the whole classification is the result not of *a priori* reasoning, but of the study of a very large number of concrete cases, embracing a wide range of circumstances and covering a large proportion of all the power transmission work that has been accomplished or proposed in this country.

CASE I. General distribution of power and light from water power. This includes something like two-thirds of all the power transmission enterprises. The cases which have been investi-

gated by the author have ranged from 100 to 10,000 HP to be transmitted all the way from one to one hundred and fifty miles. The market for power and light is usually uncertain, the proportion of power to light unknown within wide limits, and the total amount required only to be determined by future conditions. The average load defies even approximate estimation, and as a rule even when the general character of the market is most carefully investigated little certainty is gained.

For one without the gift of prophecy the attempt to figure the line for such a transmission by following any canonical rules for maximum economy is merely the wildest sort of guesswork. The safest process is as follows: Assume an amount of power to be transmitted which can certainly be disposed of. Figure the line for an assumed loss of energy at full load small enough to insure good and easy regulation, which determines the quality of the service, and hence, in large measure, its growth. Arrange both power station and line with reference to subsequent increase if needed. The exact line loss assumed is more a result of trained judgment than of formal calculation. It will be in general between 5 and 15 per cent., for which losses generators can be conveniently over compounded. If raising and reducing transformers are used the losses of energy in them should be included in the estimate for total loss in the line. In this case the loss in the line proper should seldom exceed 10 per cent. A loss of less than 5 per cent. is seldom advisable.

It should not be forgotten that in an alternating circuit two small conductors are generally better than one large one, so that the labor of installation often will not be increased by waiting for developments before adding to the line. It frequently happens, too, that it is very necessary to keep down the first cost of installation, to lessen the financial burden during the early stages of a plant's development.

CASE II. Delivery of a known amount of power from ample water power. This condition frequently arises in connection with manufacturing establishments. A water power is bought or leased *in toto*, and the problem consists of transmitting sufficient power for the comparatively fixed needs of the works. The total amount is generally not large, seldom more than a few hundred horse power. Under these circumstances the

plant should be designed for minimum first cost, and any loss in the line is permissible that does not lower the efficiency enough to force the use of larger sizes of dynamos and water wheels. These sizes almost invariably are near enough together to involve no trouble in regulation if the line be thus designed. The operating expense becomes practically a fixed charge, so that the first cost only need be considered.

Such plants are increasingly common. A brief trial calculation will show at once the conditions of economy and the way to meet them.

CASE III. Delivery of a known power from a closely limited source. This case resembles the last, except that there is a definite limit set for the losses in the system. Instead, then, of fixing a loss in the line based on regulation and first cost alone, the first necessity is to deliver the required power. This may call for a line more expensive than would be indicated by any of the formulæ for maximum economy, since it is far more important to avoid a supplementary steam plant entirely than to escape a considerable increase in cost of line. The data to be seriously considered are the cost of maintaining such a supplementary plant properly capitalized, and the price of the additional copper that will render it unnecessary. Maximum efficiency is here the governing factor. In cases where the motive power is rented or derived from steam, formulæ like Kelvin's may sometimes be convenient. Losses in the line will often be as low as 5 per cent., sometimes only 2 or 3.

CASE IV. Distribution of power in known amount and units, with or without long-distance transmission, with motive power which, like steam or rented water power, costs a certain amount per horse-power. Here the desideratum is minimum cost per HP, and design for this purpose may be carried out with fair accuracy. Small line loss is generally desirable unless the system is complicated by a long transmission. Such problems usually or often appear as distributions only. Where electric motors are in competition with distribution by shafting, rope transmission, and the like, 2 to 5 per cent. line loss may advantageously be used in a trial computation.

The problem of power transmission may arise in still other forms than those just mentioned. Those are, however, the commonest types, and are instanced to show how completely

the point of view has to change when designing plants under various circumstances. The controlling element may be minimum first cost, maximum efficiency, minimum cost of transmission or combinations of any one of these, with locally fixed requirements as to one or more of the others, or as to special conditions quite apart from any of them.

In very many cases it is absolutely necessary to keep down the initial cost, even at a considerable sacrifice in other respects. Or economy in a certain direction must be sought, even at a considerable expense in some other direction. For these reasons no rigid system can be followed, and there is constant necessity for individual skill and judgment. It is no uncommon thing to find two plants for transmitting equal powers over the same distance under very similar conditions, which must, however, be installed on totally different plans in order to best meet the requirements.

As regards the general character of transmission lines the most usual arrangement is to employ bare copper wire supported on wooden or iron poles by suitable insulators. Now and then underground construction becomes necessary owing to special conditions. Not infrequently an aërial transmission line must be coupled with underground distribution owing to municipal regulations. Occasionally insulated line wire is used. It is frequently employed in cases where the transmission lines are continued for purposes of distribution through the streets of a town, in fact, is usually required. As such lines are generally of moderate voltage, very seldom exceeding 3,000 volts, good standard insulation may often be effective in lessening the danger to life in case of accidental contacts, and in reducing the trouble from crossing of the lines with other lines, branches of trees, and the like. In case of really high voltages, 5,000 to 10,000 and upward, no practicable insulation can be trusted for the former purpose, and may in fact create a false sense of security, while it is far better practice to endeavor to avert the danger of short circuits than to take extraordinary precautions to mitigate their momentary severity. Hence bare copper is to be preferred both on the score of safety and of economy.

Much can be said in favor of placing a transmission line underground, but there are also strong reasons against it.

Such a line is eminently safe and free from danger of accidental injury. At the same time it is very difficult to insulate properly, and if trouble does arise it is exceedingly hard to locate and difficult to remedy. In addition, there are serious electrical difficulties to be encountered, which often can be reduced only by very costly construction. The chief objection aside from these is the expense, which in very many cases would be simply prohibitive.

In cities there is an increasing tendency on the part of the authorities to demand underground construction. Overhead wires are objectionable on account of their appearance, danger to persons and property, and their great inconvenience in cases of fire, and these objections apply with almost equal total force to all such wires, whether used for electric light or power, or for telegraphic and telephonic purposes, the latter making up by their number for any intrinsic advantage in the matter of safety. The future city will have its electric service completely underground, at least in the more densely inhabited portions. It must be said, however, that it is more important for a city to have electric light and power than to insist on having it in a particular way, and unless the service is very dense, so as to abundantly justify the very considerable added cost of underground work, private capital will hesitate to embark in an enterprise so financially overloaded.

Fortunately, for city distribution moderate voltages must be employed on account of the intrinsic limits of direct current circuits employed for general distribution, and the undesirability of distributing transformers of moderate size on very high pressure alternating circuits. More than 2,000 to 3,000 volts, save on arc circuits, can seldom be used advantageously in general distribution, and such voltages can be and are successfully insulated without prohibitive expense. They work well in practice, and have stood the test of considerable experience. Moreover, with proper care the cables employed as conductors, when thoroughly protected and inspected, probably have a less rate of depreciation than overhead insulated lines, and are less liable to interruption. As the district within which underground service is necessary is usually of no great extent, the electrical difficulties that are to be dreaded in attempting long underground transmissions are not here of serious magnitude.

For this limited service, then, in districts where both population and service are dense, there is no inherent objection to underground lines, and many who have used them are decided in commending them as on the whole more convenient and reliable than aërial lines. Besides, a large proportion of underground work is done at low voltages, less than 250 volts, with which the difficulties of insulation except at joints are really trivial. Such work does not belong so much to power transmission proper as to distribution from centers after the transmission is accomplished.

With high voltages and long distances the case is very different. Not only are the difficulties of insulation great, but electrical troubles are introduced of so severe a character as to make success very problematical, even in cases where the cost alone is not prohibitive. The feat of cable insulation for pressures as great as 10,000 volts has been accomplished, and this limit could probably be exceeded, but the cost of such work is necessarily high, and the location and repair of faults is troublesome. An overhead line is so much easier to insulate and to maintain that nearly all power transmission will probably continue to be done by this method for some time to come, until, indeed, there are revolutionary changes in underground work of which we now have no suggestion. The possibility of a long interruption of service while a fault is found and repaired is too unpleasant a contingency to be incurred. Duplicate lines are a natural recourse in such case, effective, but very costly. Aërial lines are much cheaper to duplicate, and the labor of finding and repairing faults is comparatively light.

For these reasons underground transmission lines should be avoided, certainly until we have had a long experience with high voltages overhead.

Throughout the foregoing it has been assumed that the conducting line is composed of the best quality of commercial copper wire. Inasmuch as other materials are occasionally proposed, it is worth while saying something about the relative properties of certain metals and alloys as conductors. Aside from silver, pure copper is intrinsically the best conductor among the metals. In fact, it is hard to say that it is not the equal of silver. Commercial copper wire is of somewhat vari-

able conductivity, since this property is profoundly affected by very small proportions of certain other substances. It used to be a most difficult matter to procure commercial wire of good quality, and in the early days of telegraphy much annoyance was experienced on this score. At present the best grades of standard copper wire have a conductivity of fully 98 per cent. that of the chemically pure metal, and even this figure is not infrequently exceeded. On account of the comparatively low tensile strength of copper, ordinarily about 35,000 lbs. per square inch, very vigorous efforts have been made to exploit various alloys of copper on the theory that their greater strength would more than overbalance the lessened conductivity and increased cost, by enabling less frequent supports to be employed. Aluminium bronze, silicon bronze and phosphor bronze have been tried, together with some other alloys of a similar character exploited under various trade names. The whole matter of high conductivity bronzes has been so saturated with humbug that it is very hard indeed to get at the facts in the case. Copper which is hard-drawn probably has greater tensile strength than any so-called bronze of similar conductivity, from 60,000 to 70,000 lbs. per square inch, with a resistance less than 5 per cent. in excess of that of ordinary copper. The following table gives the conductivities and tensile strengths of some of the various materials used or proposed for line wire, pure copper being taken as the standard at 100 per cent. conductivity :

MATERIAL.	CONDUCTIVITY.	STRENGTH, LBS.
Commercial copper wire......	98–99	35,000
Good hard-drawn copper......	96–97	60,000–65,000
(1) Silicon bronze............	97	63,200
(2) Silicon bronze	80	76,000
(3) Silicon bronze............	45	110,000
Phosphor bronze...	26	101,000
Iron annealed wire.......	14	55,000
High carbon steel wire........	10–12	120,000–130,000

It is sufficiently evident from this table that where the best combination of strength and conductivity is wanted, hard-drawn copper is unexcelled. For all ordinary line work good annealed

copper wire is amply strong, and is, besides, easier to manipulate than wire of greater hardness. Occasionally, where it it desirable to use extra long spans, or excessive wind pressure is to be encountered, the hard-drawn wire is preferable. Now and then, in crossing rivers or ravines, spans of great length are desirable,—several hundred yards,—and in these cases one may advantageously employ silicon or other bronze of great tensile strength, or as an alternative a bearer wire, preferably a steel wire cable, carrying the copper conducting wire.

Compound wires have now and then been used, consisting of a steel core with a copper covering. They are, however, costly and no better than hard-drawn copper for line use. Iron is the only material that replaces copper to any extent. It is cheaper for equal conductivity, but in wire is far less durable, and in rods cannot be strung overhead conveniently, while, even were this possible, the difficulty of making and maintaining joints is most serious. In rare cases iron may prove useful, but for all regular line work copper is the only material to be seriously considered.

Before taking up the practical task of line calculation it is necessary to consider somewhat at length the electrical difficulties that must be encountered, and which impose limitations on our practically achieving many things that in themselves are desirable and useful. We have seen already that the secret of long distance transmission lies in the successful employment of very high voltages, and whatever the character of the current employed, the difficulties of insulation constantly confront us. These are of various sorts, for the most part, however, those that have to do with supporting the conducting line so that there may not be a serious loss of current *via* the earth. Next in practical importance come those involved in insulating the conductor as a whole against, first, direct earth connections or short circuits in underground service, and second, grounds or short circuits, if the line is an aërial one.

In a very large number of cases no attempt is made to insulate the wire itself by a continuous covering, and reliance is placed entirely on well-insulated supports. In most high voltage lines this is the method employed, partly for economy but chiefly because there is well-grounded distrust in the durability of any practicable continuous covering under varying

climatic conditions and the constant strain imposed by high voltage currents.

So far as supports go, it is evident that while the individual resistance of any particular one may be very great, the total resistance of all those throughout the extent of a long line to which they are connected in parallel to the earth, may be low enough to entail a very considerable total loss of energy. The possibility of such loss increases directly with the number of supports throughout the line. The most obvious way of reducing such losses would be to considerably increase the distance between supports. This process evidently cannot go on indefinitely, for mechanical considerations, and hence the greatest advance can be made in reducing the chance of loss in individual supports.

Most of the present practice consists merely of an extension of the methods that were devised for telegraphic work. These were quite sufficient for the purpose intended, but are inadequate when applied to modern high voltage work.

The ordinary line consists, then, of poles, bearing on pins of wood or metal secured to cross arms, bell-shaped glass or porcelain insulators. To grooves on or near the top of these the line wire is secured by binding wire. Loss of current to earth in a line so constituted takes place in two ways. First, the current may pass over the outer surface of the insulator, up over the interior surface, thence to the supporting pin and so to earth. Second, it may actually puncture the substance of the insulator and pass directly to the supporting structure.

The first source of trouble is the commoner, and depends on the nature and extent of the insulating surface, and even more on climatic conditions. The second depends on the thickness and quality of the insulating wall which separates the wire from the pin. To avoid leakage an insulator should be so designed that, first, the extent of surface shall be as long and narrow as possible; second, that this surface shall be both initially and continuously highly insulating. The first condition is met by making the insulator of comparatively small diameter, and adding to the length of the path over which leakage must take place by placing within the outer bell of the insulator one or more similar bells (usually called petticoats). These not only help in the way mentioned, but they are likely

to be tolerably dry even when the exterior surface is wet, and thus help to maintain the insulation.

A good glass or porcelain insulator made on these general lines gives excellent results with ordinary moderate voltages, say up to 3,000 volts. When the insulators are new and clean they will quite prevent perceptible leakage, and for the voltages mentioned are satisfactory under all ordinary conditions. When higher voltages are employed the results may be at first good, but they are unlikely to stay so unless the climatic conditions are exceptionally favorable. Most glass permits a certain amount of surface leakage, even when new, although generally not enough to be of practical importance, but even the best glass weathers when exposed to the elements, so that in time the surface becomes slightly roughened and retains a film of dirt and moisture that is a very tolerable conductor. Even while perfectly free from this deterioration at first, it is generally hygroscopic, because it is in a trifling degree soluble even in rain water, and tends to retain a slight amount of moisture. Thus in damp climates glass is likely to give trouble when used on a high voltage line. As regards temporary fall in insulating properties, a searching fog or drizzling rain is worse in its effects on insulators than a sharp shower or even a heavy rain, which tends to wash the outer surface free of dirt, and affects the comparatively clean interior but little.

Much cheap porcelain is also hygroscopic owing to the poor quality of the glaze, and it has the considerable added disadvantage of depending on this glaze for much of its insulating value. Glass is homogeneous throughout its thickness, while porcelain inside the glaze is often porous and practically without insulating value. Nevertheless porcelain which is thoroughly vitrified, the ordinary glaze being replaced by an actual fusing of the surface of the material itself, is decidedly preferable to glass, being tough and strong, quite non-hygroscopic, and of very high insulating properties. The surface does not weather, and the insulation is well kept up under all sorts of conditions. If the vitrification extends, as it should, considerably below the surface, the insulator will resist not only leakage, but puncture, better than any glass. The process of making this quality of porcelain is somewhat costly, since the baking has to be at an enormous temperature and

long continued, but the result is the most efficient insulating substance in use.

Surface leakage is more to be feared than puncture at all voltages, since the absolute insulation strength of the material can be made high enough, by careful attention to quality and sufficient thickness, to withstand any voltage within our command, and that continuously, barring mechanical injury. But leakage can never be depended on; it is a function of moisture, drifting dust, and things meteorological generally, besides which, it may take place in serious amount at voltages which otherwise would be very easy to work with.

As the result of all recent experiments, it may be confidently stated that danger from actual breaking down of the insulation by puncture need not be at all feared up to certainly 15,000 volts with any good modern high voltage insulator. With the best insulators at present attainable the voltage just mentioned can easily be doubled without serious danger of breaking through the material.

At such high electrical pressures, however, the difficulty of stopping surface leakage becomes formidable, especially in bad weather. Glass insulators become almost useless, and only the best porcelain is to be trusted—even this with some reservations. To reinforce the insulation of the surface it has been quite usual to take recourse to the extraordinary insulating properties of heavy mineral oil. Imagine the lower edge of the outer bell of any insulator folded inward so as to form a deep groove opening upward all around the insulator. Fill this hollow with oil, and it is evident that if surface leakage takes place at all it must be across the surface of this oil.

Such an oil insulator is quite free from surface leakage so long as the oil surface is kept clean and in good condition. This is, however, very difficult to do and there is great danger that the oil surface, from the combined action of dirt and moisture, will degenerate into a species of conducting slime. Where dust is very prevalent the oil is specially likely to give trouble; it is far better able to cope with moisture alone than with moisture *plus* dust. From what has been said it is clear that line insulation is largely a matter of climate. Where it is uniformly warm and dry almost any kind of insulator will suffice, provided the material has tolerable insulation strength

and the insulator is of passably good design. With a climate foggy in summer and sleety in winter, even the best porcelain insulators will be severely tried at high voltages.

The record of what has actually been done in the transmission of electrical energy at high voltages is comparatively short, and gives no very complete data for the important work over long distances that must be done in the next few years. The experience with arc light circuits at 5,000 volts or above, working over lines from 20 to 40 miles long, is already considerable. Seventy-five to 125 light dynamos are now common, the latter giving in the vicinity of 6,250 volts, and this from open-coil armatures of which the maximum voltage is roughly equal to that of an alternator of the same nominal voltage. The lines are usually—almost always—of wire having no very high insulating properties, supported on common glass insulators, often without an interior petticoat. One hundred and fifty light generators are in occasional use, and now and then two machines of 75 lights capacity or more are operated in series for considerable periods. This practice is commoner than is generally supposed.

Alternating circuits of 5,000 volts or more are now not at all uncommon either here or abroad. Several of them have been in operation long enough to be thoroughly tested. An 18-mile transmission at a little over 5,000 volts, to Guadalajara, Mexico; an 11-mile 6,000 volt line to Hartford, Conn., and the Tivoli-Rome plant, 18 miles at 5,000 volts, have now been in steady and successful operation for several years. A number of others, probably a score in all, of less prominence, owing to shorter length of lines and smaller capacity, are in regular operation at 5,000 to 6,000 volts. Most of the lines are of bare copper wire supported on plain insulators of glass or porcelain. They have been uniformly free from all serious trouble.

In the vicinity of 10,000 volts the experiments are fewer, but none the less conclusive. Only a few commercial plants have been actually operated at such a pressure. One is the well-known Ferranti station, working a 10,000-volt main from Deptford to London, about 11 miles, and using a concentric underground cable. The plant has experienced various vicissitudes and has not been regularly operated, but the troubles

are not generally chargeable to the mains, which have, however, been a little uncertain in their performance. Another case is the lighting plant in San Antonio Cañon, California. This consists of a single alternating generator of 150 KW at 1,000 volts. Raising transformers establish a line pressure of 10,000 volts, at which current is transmitted to Pomona, 16 miles distant, and to San Bernardino, 28 miles. At each of these places is a sub-station with reducing transformers and regulating apparatus. The current is used exclusively for lighting, and the plant has been in thoroughly successful operation for about four years. The line is of bare copper supported on good-sized, double-petticoat glass insulators without oil. There has been practically no trouble from leakage, even during the winter, when rains are of almost daily occurrence, no insulators have been punctured, and the only trouble on the line has been of a very trifling character, and due to accidental causes, such as a tree branch, an occasional insulator broken by a charge of shot and the like. The line has been worked long enough to develop any probable latent trouble, and is a sufficient demonstration of the entire practicability of 10,000-volt transmission of energy, at least in a favorable climate. A third case is the Folsom Sacramento plant in California, now in operation at 11,000 volts for more than a year without trouble. Other plants at Niagara Falls, Fresno, Cal., Salt Lake City, Pachuca, Mex., and a few other points are running successfully at 10,000 to 11,000 volts.

Of systems operated at much more than 10,000 volts there is at present but one, but experiments have been not infrequent and generally successful. The most noted of these is the Lauffen-Frankfort line, 108 miles long (three-phase), worked somewhat irregularly during the latter part of the summer of 1891. Operations were generally at 13,800 volts, though on a few occasions this was temporarily doubled. There was no noticeable leakage, but an insulator was now and then punctured even at the lower pressure, producing a tiny, irregular hole clear through from the neck of the insulator to the supporting pin. The insulators which supported the bare copper line were of porcelain with oil grooves. The line worked well in all sorts of weather, but the total period of operation was too short to give this brilliant experiment much value as

a precedent. A three-phase transmission at 14,000 volts, 14 miles to the works of the Oerlikon Company near Zurich, has been in successful operation for the past three years.

Most of the large electrical manufacturing companies have during the last few years carried on experiments on high-voltage transmission, mostly with short lines near their factories. The range of voltages has varied from 10,000 to 25,000 or 30,000, and the concurrent experience has been that at the lower pressure mentioned successful working can be attained under almost any circumstances. At 15,000 volts indications are still very favorable, but at pressures of about 20,000 insulation begins to be very troublesome, both from extensive leakage in bad weather and occasional puncture. Here porcelain shows its marked superiority, and special insulators of this material can be depended on to keep down leakage and resist puncture at more than 20,000 volts under ordinary circumstances. There has not yet been enough experimentation at these higher limits to determine the probable effects of time and bad weather. The most striking experiments in this line were carried out during the year just past at Telluride, Col., under the direction of the Westinghouse Company. A line mostly composed of common telegraph wire, and about 3.5 miles long, has been worked successfully for considerable periods at pressures up to 55,000 volts, transmitting a little less than 100 HP to a synchronous monophase motor. Various kinds of insulators have been tried, including several makes of porcelain and glass. The best results have been obtained from highly vitrified porcelain and from the special glass insulators used in the San Antonio Cañon plant. Poor porcelain appears to be inferior to common Western Union glass insulators. At 55,000 volts the line wires are luminous at night with a pale blue haze, and the tie wire forms a halo about each insulator. The static strain can be plainly felt in riding under the line, producing the customary bristling effect on the hair. The loss of energy from leakage is trifling, however, under ordinary conditions, and throughout these experiments it has plainly appeared that the difficulties of working at such voltages, while considerable, are yet much less formidable than had previously been supposed.

Let us now sum up our present knowledge of the transmis-

tion of electrical energy over high voltage lines. From a considerable amount of experience, we are sure that there is no real difficulty in establishing and maintaining adequate insulation of either direct or alternating currents up to an effective pressure of 10,000 volts. Above this the experiments are less numerous, but there is every reason to believe that satisfactory results can be reached up to 15,000 without very extraordinary precautions. With good climatic conditions 20,000 or 25,000 may be considered practicable, but involve unusual precautions, not yet fully determined by experience.

At still higher voltages the difficulties are likely to multiply rapidly, and a point will ultimately be reached at which the cost of insulating devices will overbalance the saving of copper due to increased voltage. This point is at present indeterminate, and will always depend on the amount of power to be transmitted, the permissible loss in the line and unknown variables involving repairs and depreciation, cost and depreciation of transformers and so on. It is quite impossible from present data to set such a limit even approximately, for we know as yet nothing of the relative difficulty of insulating voltages considerably above the range of our experience. Only guesses are in order as to the availability of very high voltages. Personally, the author would not hesitate to undertake a transmission at 30,000 volts effective pressure in a climate like that of southern California, with the full belief that the task would be successfully accomplished. The next few years will show great progress in this direction.

In cases where continuous insulation is employed, it is for one of two purposes. Chiefly, to prevent interference with the circuit by such accidents as twigs or wires falling across the line, and either short circuiting the lines or grounding them. Aside from this, the only other object in insulation is to lessen the danger to persons accidentally touching the wires and to prevent the current straying to other circuits.

With moderate voltages both these ends can be reached with a fair degree of success. With high voltages it is very difficult, and in many cases well-nigh impossible.

Nearly all materials which are available for insulation deteriorate to a very marked extent when exposed to the weather. Those substances which are the best insulators,

such as porcelain, glass, mica, and the like, cannot be used for continuous insulation, and, in fact, our best insulators are mechanically so bad as to be impracticable. There is a large class of insulators complicated in chemical constitution, but mechanically excellent; these are the plastic or semi-plastic substances like gutta-percha, India rubber, bitumen, paraffin and the like. All of these are subject to more or less decomposition, more particularly those which are, through good mechanical qualities, desirable for insulation. All which have been mentioned are sufficiently good insulators to answer every practical requirement, if they do not deteriorate.

Gutta-percha and India rubber are decidedly the best of these; but gutta-percha is too plastic at anything excepting low temperatures to be mechanically good. Gutta-percha fills, however, an unique place on account of its remarkable ability to withstand the action of salt water, and it is the most reliable insulator for submarine work. For overhead work it is nearly useless, as the heat of the sun softens it so as to endanger its continuity, and even a moderate increase in temperature may decrease its specific resistance to a tenth of its ordinary value.

India rubber is, by all odds, the best all around insulator for overhead lines. In its pure state it deteriorates with very great rapidity; but when vulcanized by the addition of a small amount of sulphur, its chemical character is so changed as to resist both spontaneous changes and those due to the atmosphere to a very considerable extent, without injury to its insulating properties. It is, however, costly, and is eventually effected by the weather. To cheapen the manufacture of insulated wire a large variety of rubber compounds are employed, consisting of mixtures of rubber with various other substances intended to give the material good mechanical and insulating qualities at less expense. These rubber compounds are inferior to pure vulcanized rubber in point of specific resistance, but make a good and substantial covering for ordinary purposes. They are very often employed for commercial work.

Insulated wires for overhead work may be divided into two classes. First, those which are so prepared as to withstand

the weather to a considerable extent and to retain high insulating properties even in bad weather. Such wires are usually covered with a pure or nearly pure vulcanized rubber, generally protected outside with a braiding of cotton saturated with some insulating compound, and serving to protect the main insulation from mechanical injury.

The second class of wires includes those in which no solid insulating material is used, but which are thoroughly protected by a covering of fibrous material saturated with compounds of rubber, bitumen, or the like. These wires are most extensively used; the insulation is good in dry weather, and fair under most ordinary circumstances, but generally inferior to those wires which are given a coating of rubber.

So far as protection of the wire from accidental contacts is concerned, either class of insulation is tolerably effective at moderate voltages until the covering becomes worn or weathered by long or hard usage.

As regards danger in touching such wires, at moderate voltages both kinds of insulation afford a fair degree of protection. At high voltages neither can be trusted, in spite of the apparently high insulation resistance. There is good reason to believe that any insulation employed on wires is greatly affected by the strain of high voltage. Tests made with the ordinary Wheatstone bridge give us no useful information as to the action of the same insulation under stresses of 5,000 or 10,000 volts. Tests made with pressures ranging up to even 500 volts show generally a noticeable, although very irregular, falling off in resistance, and the higher the voltage is carried the more likelihood of complete breaking down of the insulation and the more irregular the results.

It is improbable that even the most careful insulation with vulcanized rubber of any reasonable thickness would give a wire which, under a pressure of 10,000 volts, could be depended on to remove all danger to persons from accidental contact. Even if entirely safe at first, it would be unlikely to remain so for any great length of time. So serious is the difficulty of continuous insulation of high pressures, that it is probably best not to place dependence upon it; but either to fall back upon bare wire with very complete insulation at the supports, or, if insulated wire be employed, to use an insulation intended only

to lessen the danger of short circuits from falling objects, and to treat it, so far as personal contact goes, precisely as though it were bare wire.

Information regarding the insulation of lines, whether of bare or insulated wire, under high voltage, is very scarce; but all such lines should be treated as if they were grounded, in spite of any tests of the insulation that may have been made. Theoretically, one should be able to touch a completely insulated circuit without danger save from static charge; but, practically, it is unsafe so to treat any high voltage circuit.

The writer calls to mind one case in which a man was instantly killed, while standing on a dry concrete floor, by contact with a 10,000 volt circuit. He probably touched a bare portion of the wire, but so far from the general insulation of the circuit saving him, the current which he received was sufficient to burn into the concrete floor the print of the nails in one of his shoes. The ordinary tests on the line made shortly afterward showed no particular ground, nor was there any reason to believe that one existed at the time of the accident. Other accidents, under similar conditions, have occurred with arc light circuits of lesser voltage, on which there was a similar absence of perceptible ground. It is advisable, therefore, that all high voltage circuits should be treated as uninsulated, so far as contact is concerned, at all times, and if insulation tests are to be made upon them to determine the resistance to grounds, these tests should be made with, at least, the full voltage of the circuit. It is quite as well not to place too much reliance on insulation of any kind; but to regard a high voltage electrical circuit as dangerous, and to be treated with the same respect as is due to other useful, but dangerous, agents, like high pressure steam and dynamite, neither of which is likely to be abandoned on account of the danger that comes from careless use. The precautions taken, either with these or with high voltage currents, should be in the direction of preventing such carelessness as might result disastrously.

An electrical circuit should be so installed that no material risk will be run by any person who is not indulging in willful interference with the line, and in such case, if an accident occurs, the victim is deserving of no more sympathy than one who deliberately stands in front of an express train.

If the circuit is of bare wire, there can be no doubt in the mind of anyone as to its dangerous character, whereas, if insulated wire is employed, there is likely to be established a certain false sense of security. There is no good reason, therefore, for advising the extensive use of insulated wire for high voltage lines.

The ideal overhead circuit is one in which the conductor is thoroughly insulated as regards leakage, carefully protected from danger of wires or branches falling across it, and placed out of the reach of anything except deliberate interference of human beings. There may be places at various points along the line where insulation would be desirable, in order to avoid extensive cutting away of trees, branches of which might fall upon the line, or where local regulations require the use of insulated wire. Except under these circumstances continuous insulation increases the cost and maintenance of the line without giving any adequate returns in security. On rare occasions, portions of the high voltage circuit may have to be placed underground. Here only the very best quality of insulation should be employed, preferably high grade rubber-covered wire thoroughly protected by an outside braiding or metallic sheathing against the effects of moisture, and installed in clean, dry, and accessible conduits. The character and amount of the precautions to be taken depend on the voltage of the circuit, and there has not yet been enough experience, at pressures above those which must be classified as moderate (that is, from 1,000 to 3,000 volts), to get sufficient data to enable one to say absolutely what are sufficient precautions. The best course to follow is, knowing the voltage at which the transmission is to be made, to select a cable which cannot be experimentally broken down by twice the voltage in question, and to install it with every precaution against deterioration. If any great work is to be accomplished, the necessary expense is so considerable as to make it well worth while to enter into a careful investigation as to the particular voltage in hand. For a transmission at 10,000 volts, for example, the writer would not consider effective any insulation less than a centimetre in thickness of the best rubber compound obtainable, and even this should be subjected to a very careful test. This suggestion is given only to point out the

general magnitude of the problem of installing cables for such voltages.

Wherever underground cables are employed, they should be subjected to a daily insulation test, and the greatest care should be taken with the joints, which are, in almost every case, the weakest point in the insulation.

From what has been said, it should be understood that while the problem of installing high voltage lines is unquestionably a difficult one, we have not yet had sufficient experience to be able to say definitely how difficult it may be. It is very certain that much more can be done than has been accomplished. It seems probable that so far as overhead work is concerned, it will be practical to employ voltages several times greater than those now in use. Before any limit can be set to the progress in this direction, we need ample experimental data, not only on the behavior of insulation at a very high pressure, but on the maximum voltage which is likely to be encountered when a certain effective voltage is to be employed. This opens up a wide field for investigation, involving conditions of unknown seriousness, connected especially with the electrical peculiarities of alternating currents, which there is every reason to believe will be employed almost exclusively on high voltage work.

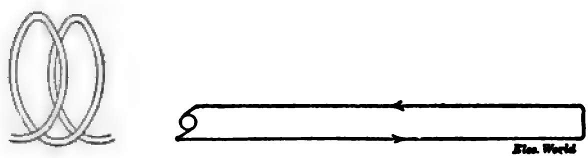
The special difficulties to be met in working with alternating currents are two—inductance in the line and apparatus, and electrostatic capacity, accompanied by the very serious phenomena of electrical resonance. In addition to these, whatever the character of the current used for transmission purposes, there is danger of getting accidentally upon the line a voltage much higher than the normal. Inductance is met with to a very considerable extent in all alternating circuits; resonance in a small degree is probably much commoner than is generally supposed, and abnormal voltage, due to the generators themselves, must always be guarded against.

Passing at once to the practical side of the question, we find that when an alternating current is sent through any conductor, it has to deal not only with the electrical resistance of that wire, but with a virtual resistance due to the fact that the electromagnetic stresses set up at any point of the conductor set up electromotive forces at other points

in the same conductor, which oppose and retard the passage of the current.

These matters have been fully discussed theoretically in Chapter IV., and hence will be here but briefly mentioned.

For example, if a wire be bent into a couple of spiral coils like Fig. 194, the electromagnetic field of one coil will affect the



FIGS. 194 AND 195.

other, just as we have induction from one separate ring to another in Fig. 4, page 12. If such a spiral has an iron core, this *self-inductance* will be much increased. Even if only a straight wire be concerned in the carrying of current, there will be a similar inductive relation between the inner and outer portions of the wire at any point, since the electromagnetic stresses exist inside the wire as well as outside.

Let Fig. 195 represent a circuit carrying an alternating current, which at a given moment is flowing as shown by the arrows. The electromagnetic field set up by this current in the loop has a direction perpendicular to the plane of the paper, and sets up an E. M. F. opposing that of the wire. The greater the area of the loop, *i. e.*, the farther apart the two wires, the greater proportion of the electromagnetic field will pass *within* the loop and produce self-induction.

Similarly, the larger the wires for a given distance between them, the less effective field within the loop to set up inductance. In fact, the amount of inductance in the circuit depends directly on the ratio between the radii of the wires and the distance between them. So if the diameter of the wire is decreased to one-half the original amount, the wires must be strung only half as far apart in order to produce the same inductance.

The practical effect of inductance in the line is to necessitate the use of an initial E. M. F. large enough to overcome the inductive loss of voltage, as well as that due to resistance, and so keep the E. M. F. at the receiving end of the line up

to its proper value. The simplest way to take account of inductance in figuring a line is to treat it as an additional resistance, which, while it does not materially increase the energy lost in the line, must be taken into one's calculation of the E. M. F. to be delivered by the generator. Its effect is to require a little greater generator capacity, *i. e.*, a machine giving, say, 1,050 volts, must be used when the effective voltage wanted is only 1,000. The combined resistance and inductance of a line is called its impedance, and this may be readily tabulated for common cases, giving the *impedance factor*—that is, the relation of the total impedance to the real line resistance. This is the easiest way of considering inductance in the line computation.

The following table gives the impedance factors for wires from 0000 to 6 B. & S., for 120 and 60 cycles per second, and for a uniform distance between wires of 18 inches. The impedance factor increases with the size of wire because the resistance decreases rapidly for larger wires; and the question of length of wire does not enter, because both inductance and resistance increase directly with the length, so that they are always proportional. The E. M. F. of inductance increases with the cycles since the field in the loop changes more rapidly, and, therefore, gives a greater induced E. M. F.

No. Wires.	Impedance Factor.	
	60 Periods.	120 Periods.
0000	2.3	4.3
000	2.0	3.7
00	1.79	3.08
0	1.53	2.54
1	1.39	2.16
2	1.28	1.85
3	1.19	1.61
4	1.12	1.42
5	1.08	1.30
6	1.05	1.21

The figures in the table are for a complete metallic circuit, consisting of two parallel copper wires, and the impedance factors may be applied at once either to determine the virtual

resistance of a given wire, or the total drop of voltage that will take place on a given circuit. Suppose, for example, that we have an alternating circuit composed of No. 1 wire, delivering 1,000 volts at the receiving station. Suppose the volts lost due to resistance alone at full load current are 90, and the plant is working at 60 cycles. Then the total loss in volts will be $90 \times 1.39 = 125.1$, and the voltage of the generator must be 1,125.1 in order to give 1,000 volts at the end of the line; and so on for any load on any size of wire. It is apparent that it is undesirable to use very large wires for high frequency alternating currents, and in some cases it is better to divide the circuit, using two No. 1 wires, for instance, instead of one No. 000.

It must not be forgotten that one of the effects of inductance is to cause the current to lag behind the E. M. F., so that for the delivery of a given amount of energy at the receiving end, a current larger than the watts divided by the E. M. F. must be delivered by the generator, which must be of corresponding capacity. This increase may amount to 10 or 15 per cent., according to the character of the load, often less, and sometimes more.

Intimately connected with this is the fact that in finding the voltage at any part of the system account must be taken of all the impedances in circuit, for they are not generally in the same phase, so that their geometrical sum is almost always less than their algebraic sum. Hence, while the impedance factor applied to the line will give correctly, neglecting line capacity, the drop produced in each line wire, the voltage across the terminals of the line will usually be different from that figured from the impedance factor applied to the line alone. This difference is, generally, not great unless there is capacity at the receiving end. All these considerations complicate the exact computation of a system, and unless its character is thoroughly predetermined, no exact computation can be made.

Practically these complications can be for the most part brushed aside in designing a plant. In very few cases will the impedance factor of a line be over 2, which means generally that the whole matter can be take care of by an increase in generator voltage of less than 10 per cent.

It should be noted that the impedance factors given can be applied at once to three-phase circuits, in which the wires are equidistant. The impedance factor of such a system is the same as that of any pair of the wires. Really the most serious practical difficulties in an ordinary alternating plant are those in which the generator is involved by inductances in the system. These are of far greater moment than the impedance factor of the line. An inductance in the system produces two effects on the generator—first, as just noted, it demands a larger current to deliver the same energy; second, it tends to beat down the E. M. F. of the machine. This effect is analogous to that produced by shifting the brushes of a continuous current generator away from the position of maximum E. M. F. (See Chapter V.)

This reaction of the armature is serious in that it not only demands a considerable increase in the exciting current, but causes a severe strain on the insulation when it suddenly ceases. It is not uncommon to find an alternator that requires on a heavy inductive load double the light-load excitation of the field. For instance, if the voltage be 2,000 on open circuit, the excitation may have to be increased on inductive load to a point that on open circuit would give 4,000 volts. If, now, this load is cut off, or the line is broken, the insulation will be exposed, momentarily, at least, to double the normal voltage.

Such generators should not be used on inductive loads or in any case where the extra strain on the insulation is important. It is perfectly easy to build a generator which requires only 10 to 25 per cent. more excitation at full and inductive load than at no load, and such machines should be used in all cases where a steady voltage under all working conditions is needed. The other type has its uses, but the general work of power transmission is not one of them. With a properly designed machine, inductive load is not to be feared.

Another possible source of danger is that under certain conditions of inductive load the reaction of the load on the generator, without materially lowering its effective voltage, may so change the shape of the E. M. F. wave as to give to it an abnormally high maximum, and thereby greatly to increase the strain on the insulation. This effect may readily occur,

but usually in so small a degree as to be of little moment. Occasionally, owing to a combination of severe inductive load and badly designed generator, the results may be somewhat formidable, the more so as the change takes place under heavy load and not, as in the case just treated, only on open circuit or a sudden light load. The rise in pressure thus produced may amount to several times the nominal voltage. The same sound principles of design that insure good regulation under changes of load will obviate any danger of this kind. In fact, most of the possible disturbing factors in alternating current work become negligible in an installation carried out with regard for the general principles of good engineering.

These abnormalities of voltage lead naturally to the consideration of another far more serious, due to the static capacity of the system. Of course, the fact that under certain circumstances capacity in the system will cause a lessening of the apparent "drop" on the line, or even overcome it altogether and show a higher voltage at the receiving end than at the generator, is already well known to the reader. This is, however, but a special, and, save for its convenience in connection with synchronous motors, a trivial case of the general phenomenon known as *electrical resonance.*

The practical importance of this has been but recently realized, although the thing itself is strictly analogous to very familiar occurrences. Suspend a heavy weight by a string a yard long or so, and then begin tapping the weight lightly with the finger. So long as the taps are irregular or bear no particular relation to the time of oscillation of the weight considered as a pendulum, the only effect will be slightly jerky vibrations. As soon, however, as the taps are so timed as to coincide with the swinging period of the weight, it will slowly get under way, and presently work up an oscillation of considerable amplitude. Each tap catches the weight at the end of the double swing started by the previous tap and augments its motion.

Every system capable of oscillation is similarly affected by impulses coinciding with its natural period, which is determined by its physical properties. This rapid growth of amplitude through synchronous impulses is generally known as resonance from the very marked way in which the phenom-

enon appears in a sounding system such as that composed of a tuning fork and the box (resonator) to which it is generally affixed.

Every electrical system has a definite period of oscillation determined by its particular properties. If we could apply an instantaneous electromotive stress to any point of it, the effect would be that the resulting strain would travel back and forth with a definite frequency until its energy would be completely exhausted by doing work on various parts of the system. The action resembles that which takes place when we strike the end of a long rod with a hammer. An impulse is sent out at a rate depending on elasticity, density, and so forth, travels to the end of the rod, is reflected, and so goes on swinging back and forth until the energy is frittered away. This corresponds to electric oscillations on open circuit.

The two properties of an electrical system which determine its vibration period are its self-induction, which is analogous to inertia, and its capacity, which resembles elasticity in the dielectric, capable of taking up and returning energy. Resistance, like intermolecular friction in the rod just referred to, determines the rate at which the vibrations will die out by yielding up their energy to the system, but has ordinarily a negligible effect on the vibration period.

This period in an electric circuit is to a close degree of approximation given by the following formula:

$$T = .00629 \sqrt{LC} = \frac{2\pi}{1,000} \sqrt{LC}.$$

In this T is the natural time period of the circuit expressed in seconds, L is the coefficient of self-induction in henrys,

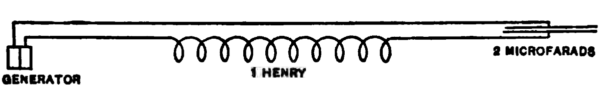


FIG. 196.

and C the capacity in microfarads. For example, suppose we are dealing with a circuit of which the capacity is two microfarads and the self-induction one henry. Let it be arranged as in Fig. 196. For simplicity the inductance and capacity are shown localized and in series as would happen if a line ran

through a group of series transformers and thence into a cable. If the line were open-circuited beyond the cable, we might find a very severe strain on the cable insulation. The period of this line would be .00887 second—about 113 cycles per second. If this should chance to be the frequency of the generator it would be in resonance with the line, and each wave of E. M. F. sent out by the generator would add itself to another wave just starting out in the same direction. A period later these two added E. M. Fs. would be reinforced by the next generator wave, and so on indefinitely.

The only thing which prevents the resultant voltage from rising indefinitely is the effect of resistance in causing each wave to die out gradually as it continues its oscillations, so that only a limited number of waves can add materially to the resultant E. M. F. across the terminals of the capacity.

In a given circuit the relation between the initial voltage and the voltage of resonance can be easily determined to a fair degree of approximation. It is, neglecting minor reactions

$$E' = \frac{n\,L}{R}\,E.$$

In this equation E' is the E. M. F. of resonance, n the frequency, L the self-induction in henrys, R the ohmic resistance, and E the initial voltage. Applying this formula to the case just discussed, and assuming the resistance of the line to be 15 ohms and the initial voltage to be 2,000, we find

$E' = \dfrac{113 \times 1 \times 2{,}000}{15} = 15{,}066$ volts. A very moderate line voltage may thus, in a resonant line, give rise to a pressure quite capable of rupturing any ordinary cable, or causing serious trouble on an overhead line, to say nothing of greatly increasing the danger to persons and property. If the working pressure were 10,000 or 15,000 volts, the E. M. F. of resonance might rise to an appalling amount.

Fortunately this theoretical value is in practice generally much reduced by hysteretic losses and Foucault currents in any iron-cored coils in circuit, waste of energy in the dielectric, and other minor causes of damping the electrical oscillations,

even when resonance is complete. Still, dangerous rises in voltage are very possible. When the frequency of the applied E. M. F. differs somewhat from the natural period of the line, resonant effects can evidently still take place, but in a rapidly lessening degree; when the oscillations are strongly damped by the presence of iron, the total resonant rise is considerably diminished, but it varies less rapidly as the resonant frequency is departed from.

A resonance curve for various capacities shows that the rise of voltage extends over quite a wide range of variation of capacity, but is large over but a small range. The shape of such a curve necessarily varies widely, as the resonance is more or less damped by resistance, iron-cored coils and so forth; but we may be quite sure that the maximum resonance will occur at not far from the point indicated by our equation for the vibration period of the circuit, and that the maximum E. M. F. of resonance will usually be considerably less than that given by the theoretical equation.

In practical alternating circuits the current wave is never truly sinusoidal, but consists of a main or fundamental wave with the odd (*i. e.*, 3d, 5th, 7th, etc.) harmonics of various amplitudes superimposed upon it. In nearly every case the third harmonic is the most prominent and is quite capable of causing resonance, even to a dangerous degree, if it happens to fall in with the frequency of the system. The extent of the rise in voltage, however, is very much less than that produced by resonance with the fundamental frequency. The point at which resonance occurs and the rise of E. M. F. are found for the harmonics by the formulæ already given.

So far as the line is concerned, the facts regarding resonance can be easily computed with tolerable accuracy. From well established data it is evident that the line capacities are generally so small as to make the oscillation period so short as not to correspond with the frequencies in ordinary use except in the upper harmonics, which are generally of small moment, although one case of severe resonance from a higher harmonic (probably the 7th) has come to the author's notice.

To facilitate computation the following table is given, showing the inductance and capacity of ordinary overhead lines per mile in millihenrys and microfarads respectively. The wires

are supposed to be of copper and to be suspended as a parallel pair at a distance of 18 inches, as in the case of the table of impedance factors. Within the range of ordinary practice varying the height above the ground makes no sensible difference in inductance or capacity.

SIZE NO.	INDUCTANCE.	CAPACITY.
0000	1.48	.0102
000	1.52	.0099
00	1.56	.0097
0	1.59	.0095
1	1.63	.0093
2	1.67	.0090
3	1.71	.0088
4	1.74	.0086
5	1.78	.0084
6	1.82	.0083

It must be remembered that not only the line capacity, but the capacity of the receiving apparatus, must be considered. The former is but small, except in the case of underground or submarine cables, for which the capacities are likely to be from ¼ to ½ microfarad per mile, as ordinarily manufactured. High voltage translating devices, like synchronous motors and transformers, often may have static capacities of several tenths of a microfarad.

As a matter of fact, experience seems to show that one is not likely to stumble upon very serious resonance in overhead lines, although in cables it is easily possible. On the other hand, it is more than likely that resonance of a minor kind, mostly from harmonics, is far commoner than is generally supposed. High pressure alternating currents often show a tendency to jump across air spaces and insulation that is hard to account for otherwise. This tendency must not be confused with the occasional displays of atmospheric electricity on overhead lines. It is not uncommon to get somewhat severe shocks from an aërial line entirely disconnected from any machinery.

The most obvious way of avoiding trouble from resonance, when it exists or is threatened, is to vary the frequency, inductance or capacity so as to throw the oscillation period of the system and the frequency of the current far apart. The fre-

quency is usually fixed by other considerations, but inductance and capacity are varied with the utmost ease. In fact, they are never constant in practice.

The readiest way of getting a clear idea of the inductance of a system is from its power factor, *i. e.*, the ratio between the apparent energy as found from voltmeter and ammeter readings and the real energy as given by a wattmeter. This not only gives the current which must be carried for a given amount of energy, but measures the angle of lag between current and E. M. F. In fact,

$$\frac{\text{Energy}}{\text{Volt-amperes}} = \cos \phi,$$

which gives the angle of lag at once. But in general

$$\text{Tan } \phi = \frac{2 \pi n L}{R}.$$

So that knowing the ohmic resistance of a circuit and its "power factor," we can get a tolerable approximation to its coefficient of self-induction, R being reckoned in ohms and L in henrys. As, however, the lag is influenced by both inductance and capacity, the formula is principally of use in connection with individual pieces of apparatus.

From a practical standpoint it is quite out of the question to compute the total inductance of a proposed system on which any resonance effects depend, with anything like accuracy, since the character and amount of the apparatus is indeterminate. One can, however, gain from experience a tolerable idea of the probable lag in a mixed system, which will at least tell whether there is imminent danger of resonance. There is really little danger at ordinary frequencies unless the static capacity involved is large—several microfarads at least.

One other phenomenon in connection with alternating current work deserves notice here. Several years ago Sir William Thomson pointed out that the ohmic resistance of a copper wire was greater for alternating than for direct currents. This is for the reason that the current density through the cross section of the conductor is not uniform when the current is an alternating one. The propagation of any current is mainly along the surface of the conductor, and only after a

measurable, though short, time is the condition of steady flow reached.

When the current rapidly alternates in direction the interior of the conductor is thus comparatively unutilized, for before the flow has settled into uniformity its direction is changed, and the original surface flow is resumed. The larger the wire and the greater the frequency the more marked this effect. Fortunately, with the common sizes of wire and the frequencies ordinarily employed for power transmission work, it is quite negligible. At 60 periods the increase of resistance due to this cause, in a conductor even half an inch in diameter, is less than one-half of 1 per cent. Any line wire that is allowable on the score of its impedance factor will be unobjectionable on this account as well. Only occasionally, as in bus bars for low voltage switchboards, is it worth considering, and in such cases the use of flat bars, half an inch or less thick, will obviate the difficulty.

We have now investigated all the important factors that enter into the design of a transmission line, whether for direct or alternating currents. Let us review them with the idea of seeing how they enter into practical cases. First comes the all-important question of initial voltage, involving the choice between the direct generation of the working pressure or its derivation from transformers, if alternating currents are used. We have already seen the practical limitations of voltage for direct currents. With alternators the commutator troubles are absent, and the limitations are those imposed by generator design. The higher the voltage of a dynamo the more space on the armature must be allowed for insulation, thereby cutting down the output of the machine. Hence the practicable voltage depends on the size of the generator.

In a general discussion it is difficult to make exact statements as to what can or cannot be done, but experience seems to show at present that 3,000 to 6,000 volts are the greatest pressures that can economically be derived from the generator, the latter only in very large units. Higher voltage than this has been attempted, but there is good reason to believe that the reduced output and increased cost of construction lead to a higher cost per KW output than if low voltage generators with transformers were employed.

For present purposes, then, we may assume that in a large proportion of cases the voltage of the generator cannot well be above 3,000 to 4,000 volts. With raising transformers 10,000 volts is known to be a practicable pressure. At some particular distance, then, in each case, the annual interest and depreciation charge against, say à 3,000 volt line, will equal the interest and depreciation charge against, say a 10.000 volt line, and its raising and reducing transformers. For a fair comparison two things must be noted—first, that 3,000 volts is an available pressure on a working circuit, so that it has the advantage over 10,000 volts, of both sets of transformers—second, that the systems must be of the same efficiency: *i. e.*, the line loss in the first case should be equal to the losses in both line and transformers in the second case.

The exact distance at which the costs by the two methods become equal must be computed from the data above outlined in each individual case on account of the variations introduced by size of units, cost of copper and transformers delivered, differing conditions of depreciation, and so on. The distance, however, is generally longer than would be at first sight supposed. Assuming an equal rate of interest and depreciation in each case, a few hundred HP as the amount transmitted and current prices of copper and large transformers, we arrive at the following approximate result: At about 7 miles, 3,000 volts from the generator and 10,000 volts with raising and reducing transformers become equal in cost. This distance rises to between 11 and 12 miles if 5,000 volts only are derived from the transformers. Generators wound for 4,000 or 5,000 volts generally will require reducing transformers for the working circuit, so that they have the advantage of the raising and reducing system by only one set of transformers.

In most cases it is desirable either to generate a voltage which can be used on the working circuit or to use from 5,000 to 10,000 volts derived from transformers. So much for the selection of a proper line voltage.

As to loss in the line much has been said already, and the best advice that can be given is to make a few trial computations along the general lines indicated. Almost every case will require special treatment in certain particulars, depending on the conditions of service. For example, a common com-

plication is the supply of power or light, or both, at a point perhaps halfway along the line. Then, according to the amount and kind of service, it may be desirable simply to tap the line, to tap the line for power and use a motor generator for lights, to establish a substation with regulating apparatus, to compound the generator for the point in question and use either of the above methods at the end of the line, to install rotary transformers, or to run a separate line with regulators at the generating station. Such details will be treated at length in Chapter XII.

The line structure should preferably be of bare copper wire carried on wooden or iron poles. Do not put it underground unless you have to do so. It may be necessary to insulate portions of the wire, but it is best not to put much faith in an insulating covering. Instead, it is desirable to make a very thorough job of insulation at the supports, and provide for the easy inspection of the line.

In using alternating currents inductance in the line must always be considered. Practically it means raising the voltage of the generator or raising transformers by a few per cent., unless a fair part of the load is in synchronous motors which can be employed to counteract the inductive drop. In nearly every case its real importance is small, in spite of its scaring the uninitiated now and then.

So, too, with the inductive load. Its real effect is merely to increase the current in the line by a small amount, usually less than 15 per cent., and to demand increase of excitation at the dynamo. If this is so designed as to regulate badly, an inductive load will render it difficult or impossible to keep a uniform voltage. On the other hand, a generator capable of holding its voltage from no load to a full and inductive load with an increase of only 15 or 20 per cent. in the exciting current will usually give no trouble whatever.

The total net result of inductance in line and load is to call for a well-designed generator with good inherent regulation and a reasonable margin of capacity. One who knowingly installs anything else deserves all the troubles that inductance can produce.

Rise in voltage, on throwing off the load or through distortion of the current wave by an inductive load, can be reduced

to insignificance by employing a proper generator as just noted. Aside from this, a mixed load, particularly if it consists in part of synchronous motors, seldom has a bad power factor or great and sudden changes in its amount.

As regards static disturbances, few overhead systems have capacity enough to give cause for alarm. Difficulties are to be looked for chiefly on very long lines, longer than any now in use, and those composed in part of underground or submarine cables. In these cases one may sometimes know the conditions well enough to calculate the actual result in rise of voltage. More often the data are incomplete, and the simplest way out of the difficulty is to try the effect of varying the capacity of the system before it goes into regular operation. If the addition of a condenser, say of one-third microfarad, makes a sharp variation in the voltage, look out for resonance and investigate the capacity of the system, step by step. A change of capacity or inductance can be made sufficient to avert any serious danger of resonance.

We may now pass to the practical calculation of a line.

CASE I.—The simplest possible case is the transmission of direct current over a short distance. Let it be required to deliver 200 HP to a machine shop for operating machinery and a small tramway over a distance of one mile and a half, power to be about equally divided between small motors and tramway. Source of power—water power—owned outright by the company, and ample in amount. Load on small motors steady, on tramway very variable. In a case of this kind the use of direct current is advantageous, since with plenty of power considerable drop can be permitted, and the use of any alternating system would involve changing to direct current for the tramway. For use in a machine shop the speed of the motors need not be very uniform, so that there will be no especial difficulties of regulation. On account of size of motors 500 to 600 volts will be the highest permissible voltage.

There are several courses open in determining the drop. The easiest is to assume for the final voltage such a value as will give the greatest drop compatible with convenient regulation, and the initial voltage delivered by a standard railway generator. A special generator is objectionable on account of both first cost and difficulty of repairs. The generator can be counted

on for 600 volts maximum. If, therefore, we run it at a normal no-load voltage of 550, and over compound about 10 per cent., we shall get no more than about 550 volts at the motors. During the time that the tramway is working we can let the voltage fall to 500, for which the tramway motors give their normal output, without interfering materially with the regulation of the other motors. We take the maximum drop, then, at 100 volts. The amount of power to be delivered at full load is 200 HP.

Taking the average commercial efficiency of the motors at 80 per cent., the electrical HP to be delivered is 250, which equals very nearly 187,500 watts at 500 volts. The current, therefore, is 375 amperes. To allow for sag, joints and accidental variations, we should take the mile as about 5,400 ft. instead of 5,280. We are now ready to determine the cross section of the wire by the formula already given. We then have

$$\mathrm{cm} = \frac{16{,}200 \times 11 \times 375}{100} = 668{,}250.$$

Looking now in our wire table, we find that the nearest convenient approach to this cross section is three 0000 wires, each of 211,600 cm. We might reinforce these by a No. 5 wire and get almost exactly the amount required, but the game is hardly worth the candle, since we are working for minimum first cost, and a very trifling increase of drop is not worth considering, particularly as the maximum load will be for only a few minutes at a time. A nominal 200 KW generator will serve our purpose if built, as standard railway generators are, to stand small and temporary overloads at any time. The cost of the copper for such a circuit is considerable; 48,600 ft. of No. 0000 will be required, weighing, when insulated, as it generally would be in running into a town, about 750 lbs. per 1000 ft. The total weight would then be 36,450 lbs., costing, at 15 cts. per lb., $5,467, quite nearly $22 per HP delivered. Occasionally it would be advisable to allow greater drop than that here assumed.

Case II. A cotton mill is operated by steam, coal costing about $5 per ton, the actual brake horse-power required to drive the machinery being 660. Speed must be constant,

load is very uniform, and any reduction of available horsepower cuts down the output, all of which is badly needed to fill contracts. A cheap water power, distant 22,000 ft., is acquired by the mill owners. Sixteen thousand cubic ft. of water per minute available, and the greatest head that can be utilized is 30 ft. At the existing price for coal electrical transmission will certainly pay. The full 660 HP must be delivered, or the power will have to be supplemented by steam, unless part of the looms are shut down.

The given amount of water will produce, when utilized in first-class turbines, almost exactly 800 mechanical HP. Two turbines are used for security against breakdown, and each runs 150 revolutions per minute. The commercial efficiency of the plant must then be at least $\frac{66}{800} = 82.5.$ per cent. Taking 300 KW units for generators and motors we can be sure of a commercial efficiency of .93 in each machine. This limits the efficiency of the line to not less than 95.4. It is evident at once that direct coupled generators must be used, since the 4 or 5 per cent. lost in belting would be quite inadmissible.

As to voltage, it is evident that the highest available in a 300 KW unit should be used. Without going into special windings, the voltage would be, say, 4,000 over compounded about 5 per cent., giving 4,200 at the brushes. At the assumed efficiency of the motors there must be delivered to them 529 KW. At 4.6 per cent. drop in the line 132 amperes must be the current. All question of inductive drop may be neglected, since the motor field can be adjusted to compensate for it. Taking the actual length of circuit at 45,000 ft., and employing the formula as in Case I., the cross section of conductor comes out as 355,100 cm.

This is very nearly met by three No. 00 B. G. W. wires. Wire drawn to this British wire gauge can be readily obtained without increased cost. The combined section of the three is but a little over 2 per cent. more than that required, hence will serve excellently. Supposing bare wire to be used, the weight of each conductor per thousand feet is 369 lbs. The total weight of copper is then 49,815 lbs., costing, at 15 cents per lb., $7,472. Any increase in the loss in the line will

cause a failure to deliver the required power and necessitate the operation of a subsidiary steam plant, or the shutting down of nearly a score of looms for each per cent. decrease in efficiency. Doubling the line loss would save $3,736, but at a cost and trouble of a 40 HP steam plant, or the loss of the output of 75 or 80 looms. In a case of this kind the easiest way of reducing the cost of line would be to use the three-phase synchronous system, or the three-wire two-phase, either of which would save a quarter of the above copper at the same efficiency. Generators and motors of more than 4,000 volts would give even better results if thoroughly reliable, as they might be for slow speed units of the size in question.

Case III. It is desired to deliver for general service in a city 1,000 KW from an ample water power 20 miles distant. Power is to be used for arc and incandescent lighting, and a motor service of unknown amount, possibly as great as 500 HP; 3,000 to 4,000 HP can be obtained at the power station; and allowance must be made for extensions.

On account of reduced cost of line the three-phase system is desirable, effecting the distribution by secondary mains at about 220 volts between wires, using a balance wire for lamps. This requires a little less than 30 per cent. of the copper needed on the two-wire system with the same voltage at lamps. Evidently raising and reducing transformers should be used, and the climatic conditions are favorable enough to allow 10,000 volts on the line. We should first decide on the generators. Four hundred KW is a convenient size, three being used for the total plant. The voltage should be moderate; say, 500 volts. With this preliminary, let us figure the line. We can conveniently lose about 10 per cent. of the energy, say, 5 per cent. in the two banks of transformers and 5 per cent. loss in the line. The voltage at the receiving end will be 9,500, with 10,000 at the raising primaries. As to regulation, the distributing system is worked from a substation where the regulating is done.

Since the copper required is three-fourths of that needed for a two-wire system at the same voltage, each of the three wires will have one-half the cross section of either wire on the two-wire system. We may, therefore, use our previous formula if we take account of this factor one-half. The simplest way of

doing it is to take the single distance of transmission instead of the double distance. As to the current in the formula, it must be the equivalent single-phase current. If we write

$$\frac{W}{V}$$

instead of C, we shall avoid all confusion on this score. Our formula then becomes

$$\text{c. m} = \frac{D \times 11 \times \frac{W}{V}}{V_1},$$

wherein D is the distance of transmission, W the watts received, V the voltage of reception, and V_1 the volts lost in the line. In our case $D = 108{,}000$ (the mile being taken as 5,400 ft.), $= V = 9{,}500$, $V_1 = 500$, $W = 1{,}000{,}000$. Then c. m. $= 250{,}000$ (nearly).

But we must remember that our load is a mixed one of lights, and probably both synchronous and induction motors. Hence it will have an inductance. Hence a current somewhat larger than that given by

$$\frac{W}{V}$$

must be taken. With fairly good luck in our proportion of lights and synchronous motors, 5 per cent. increase will be enough to allow. At worst it could hardly be greater than 10 per cent., which would mean a very small increase in ohmic drop. Taking it at 5 per cent., we add that amount to our cross section and obtain 262,500 c. m. The nearest approach to this with standard wires is two No. 00 = 266,000 c. m.

Now as to inductive drop. At worst the impedance factor of the line will not be greater than 1.79, with 60 periods and wires strung 18″ apart. Therefore, a rise of less than 4 per cent. in our generator voltage will take care of the inductance in the line. As to capacity, each pair of wires will have a capacity of less than $\frac{1}{100}$ microfarad per mile, so that we need not borrow trouble on the score of resonance. The effect of total inductance on the generator is small, since the power factor of the system is likely to be as great as .95, and if the

generator is even tolerably well designed, a few per cent. increase in excitation will compensate for this. Now computing the total amount of copper we find it to be 261,144 lbs., costing, at 15 cents per lb. for bare wire, $39,171.

A very simple and accurate formula for giving the total weight of a three-phase circuit directly, neglecting inductance, is

$$W = \frac{100\, D^2_m \frac{W}{V}}{V_1}.$$

We now have a working line laid out, and feel sure that no contingencies we are likely to meet will cause the drop to vary much from 5 per cent., since within the probable range of power factor that can be found in a mixed plant both line and generators are well able to take care of the variations. The net result of inductance has been to increase our allowance of copper by 5 per cent., and to require 10 or 15 per cent. margin of excitation and current capacity in our generator.

This may seem a rough and ready process for figuring a transmission line, but it gives a safe and conservative result as nearly exact as the data generally available for a new plant permit. If the capacities and inductances of the future system could be predetermined, we could take their vector sum and compute a small correction to our factor of safety in the generator. If the future load were exactly known we might wish to change the drop slightly. No exact data are available under ordinary circumstances, hence we must rely on our judgment in selecting the drop and factor of safety in the generator, which, unless it be downright bad in design, will have margin enough to meet any reasonable requirements.

CHAPTER XI.

LINE CONSTRUCTION.

THE first consideration is the general question of location. Other things being equal it is obvious that a direct line is the best, but as a matter of fact it is seldom altogether practicable. A line must above all things be secure against interruptions, and with this in view both the location and the constructional features should be determined.

In smooth and easy country a nearly straight line can usually be laid out. For large plants carrying large amounts of power at high voltages it is often desirable to buy the right of way outright. Such has mainly been the policy pursued in the transmission from Niagara to Buffalo, and, while expensive, it gives an absolute command of the situation. In some States electric light and power companies are given the right of eminent domain to make such ownership possible.

In cases wherein the purchase of such a location is impracticable or would involve very serious expense the next best thing is to secure right of way along the public roads, so far as they can be conveniently utilized, and right of way for the pole line through such private property as may be in the contemplated route. Rights along the public roads are very desirable, as giving capital facilities for line inspection and repair without expense. Right of way merely for the line across private lands, with proper facilities for access, can generally be cheaply secured. Many owners are public-spirited enough to give it for the asking, or for very reasonable compensation when a strip of land has to be taken for a roadway.

In small transmissions the public roads are most desirable as a route, using private lands only for occasional short cuts.

Since a good road along the pole line is highly desirable, the route should be taken through clear and accessible country, so far as is possible.

Places to be avoided when possible, even by a detour, are

marshes, where poles are always hard to set and maintain and roads are difficult to construct; heavily wooded country, where there is constant danger to the line from falling branches and the like; and rough rocky slopes, where construction is difficult and the line, when constructed, is highly inaccessible. Sometimes the topographical conditions are such that these difficulties have to be met, but they are always serious.

In a wooded region the only proper plan is to secure right of way broad enough to permit clearing away the trees so that they cannot interfere with the line wires, even were branches to be blown off in a storm. Nothing short of a hurricane sufficient to blow down large trees should possibly be able to cause trouble, and when the neighboring trees are dangerously high careful watch should be kept and any weak or decaying tree at once cut down. The right of way may be somewhat expensive, but the service must not be liable to interruption by so probable a thing as the breaking of a branch. Sometimes the use of extra long poles may enable one to carry the wires clear of possible obstructions of this sort.

In mountainous regions poles may have to be set in very bad locations, and sometimes for long stretches every hole may have to be blasted at a cost of $10 to $20 per hole, but such contingencies are not very common and may often be avoided by a moderate detour. It is better to go around a mountain than over it, unless the distance is considerably greater. When these questions arise they should be answered by preliminary estimates. The country should be carefully inspected and the relative costs of various routes looked into. For a uniform country the cost of poles and construction is directly as the distance, and the cost of copper directly as the square of the distance.

In case the direct line leads into difficult country—over, for example, a rocky hill where the poles would be hard to place and much blasting would have to be done—a detour often may cheapen construction. A brief computation will give the facts. Suppose a 10-mile transmission of about 500 KW at 10,000 volts, for simplicity assumed to be on the monophase system. The line would have to be about No. 0 wire for say 6

per cent. loss, and the total weight of copper would be about 33,000 lbs. Suppose the average cost of poles and insulators in position to be $5 in the open country, but the direct route lies for a mile over a rough hill, where holes would have to be blasted and poles are difficult to get into place. The extra cost of this mile might readily be $500 to $600. Now if a deviation of a mile would clear this hill, it would probably pay to abandon the direct route. By taking the shortest available course the actual increase in the length of the route would not often exceed half a mile. This would increase the weight of copper for the same loss by about 10 per cent., $495 at 15c. per lb., and would increase the cost of the pole line by about $250 more. In such a case the increased accessibility of the line, and the lessened cost of providing a road for inspection and repairs, would more than compensate for the small difference in expense. The same reasoning holds with respect to avoiding other obstacles by making detours. It often pays to go somewhat out of the way to utilize the public roads, to cross rivers on existing bridges, and so forth. A few experiments on the route constructed on paper, after careful inspection of the country, will usually show the most advantageous line to follow. The old and simple process of sticking pins in the map and following up the line with thread is generally the easiest way of getting the various distances.

In mountainous country a direct line is often out of the question, and the line has to conform to existing trails with such short cuts as may be possible. An occasional long span will sometimes lessen the cost of the line materially. Rivers and lakes often form very serious obstacles to line construction and call for much skillful engineering. The former can often be crossed on existing bridges or by long spans, which will be discussed later, but the latter usually have to be gone around, although sometimes cables may have to be carried under water. If the lake is close to either end of the line, so that it can be crossed by a cable at moderate voltage, it is sometimes advisable to do so. In two important cases that have come to the author's notice this was the only practicable escape from the watery barrier.

Nearly all long lines have to encounter more or less serious obstacles of the sorts mentioned, and as a rule they

cause considerable deflections from a straight course. Sometimes deviations are desirable merely as the cheapest way of reaching en route localities where power is to be distributed.

LINE WIRE.

As already mentioned copper is the best and most usual material for conductors; soft-drawn copper under ordinary circumstances, hard-drawn when extra strength is desirable. No other material gives so advantageous a combination of conductivity and tensile strength for nearly all purposes. The tensile strength of the copper is raised by hard drawing from about 34,000 to 35,000 lbs. per square inch to 60,000 or even 70,000, and the resistance is only raised 2 to 4 per cent., the latter only in small sizes.

For line copper the wire should be free from scale, flaws, seams, and other mechanical imperfections. It should be very close to its nominal gauge, variations of 1 to 2 mils being the largest which should be tolerated, and should be very close to standard conductivity, as given for pure copper in tables of wire.

The following table gives the electrical and mechanical constants of the sizes of wire used in power transmission work:

Gauge B. & S.	Diameter Mils.	Area Circular Mils.	Wt., Lbs., per 1,000 Feet.	Resistance at 75° F. per 1,000 Ft. Ohms.	Tensile Strength (Ultimate) Based on 34,000 Lbs. per Sq. In.
0000	460,000	211,600	640.73	.04904	5,640
000	409.640	167,805	508.12	.06184	4,480
00	364,800	133,079	402.97	.07797	3,553
0	324,950	105.592	319.74	.09827	2,819
1	289,300	83,684	253.43	.12398	2,235
2	257,630	66,373	200.88	.15633	1,772
3	229,420	52,633	159.38	.19714	1,405
4	204,310	41,742	126.40	.24858	1,114
5	181,940	33,102	100.23	.31346	884
6	162,020	26,250	79 49	.39528	700
7	144,280	20,816	63.03	.49845	556
8	128,490	16,509	49.99	.62849	440

The various constants should none of them fall short of these tabulated values by more than 2 per cent. Specially, the resistances should not be in excess of those given by more than this amount.

For hard-drawn copper wire the resistance never ought to exceed the tabular values by more than 5 per cent. and the tensile strength should not fall short of 1.75 times the values given for annealed wire.

When in use, wire is subject to serious mechanical strains, due in the first place to its weight and normal tension, second to variations in tension by change of temperature, and third to extraneous loads like ice and wind pressure, separately or combined. These last-mentioned strains are sometimes formidable and must be carefully taken into account, particularly in cold climates.

When a wire is suspended freely between supports it takes a curve known technically as the catenary. The exact solution of its properties is very difficult, but for the case in hand the catenary comes very close to the parabola, a much simpler curve to compute; and based on this approximation the following simple deductions can be made: If a wire be stretched

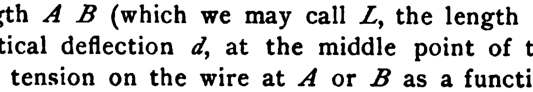


FIG. 197.

between the points A and B, Fig. 197, it assumes the curve $A\,D\,B$. The thing to be determined is the relation between the length $A\,B$ (which we may call L, the length of span), the vertical deflection d, at the middle point of the span, and the tension on the wire at A or B as a function of its weight. This relation is as follows:

$$T = \frac{L^2 w}{8 d}, \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

or transposing,

$$d = \frac{L^2 w}{8 T}. \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Here L is the length of the span in feet, d the central deflection in feet, w the weight of the wire in pounds per foot, and T the maximum tension on the wire in pounds.

These equations show that with a given wire the tension varies inversely as the deflection for a given span, and that for a given tension and wire, the deflection must increase with the square of the span. Obviously, shortening the span and increasing the deflection eases the strain on the wire and renders the construction more secure, but shortening the span adds considerably to the cost, and increasing the deflection increases the danger of the wires swinging in the wind and touching each other. To prevent this the deflection should not much exceed twice the horizontal distance between wires.

The application of the formulæ can best be shown by an example. Suppose we are stringing No. 00 wire on poles 100 feet apart. What is the least deflection allowable with a factor of safety of 4? This means that T must not exceed one-fourth the breaking strain of the wire, which fraction from the table is 888 lbs. The weight per foot from the table is .4 lb. Substituting in equation (2) we have:

$$d = \frac{(100)^2 \times .4}{8 \times 888} = .57 \text{ foot} = 6.8 \text{ inches.}$$

This minimum deflection should not be exceeded in this case, and hence must be applicable to the lowest temperature to which the line is to be exposed. At whatever temperature the wire is strung, enough deflection should be allowed so that, as the wire contracts in cold weather, the above minimum should not be passed.

The total length of wire in the catenary is approximately

$$L^1 = L + \frac{8\,d^2}{3\,L}, \qquad \ldots\ldots\ldots\ldots\ldots (3)$$

or transposing for the value of d,

$$d = \sqrt{\frac{3\,L\,(L^1 - L)}{8}}. \qquad \ldots\ldots\ldots\ldots (4)$$

Wherein L^1 is the actual length of wire, and L the span.

From these formulæ we can figure d for any temperature.

The coefficient of expansion of copper is .0000095 of its length per degree Fahrenheit, so that we can get at once the length for any temperature.

If the wire we are considering is strung at 75° F. and is to encounter a minimum temperature of −5° F., enough deflec-

tion must be allowed at the former temperature to bring the deflection at $-5°$ F. to the value just obtained. The length of wire at the lower temperature is from (3),

$$L^1 = 100 + \frac{8\,(.57)^2}{300} = 100.0096.$$

At 75° F. this length would be increased by $100.0086 \times .0000095 \times 80$ feet, and hence the new value of L^1 would be 100.076 feet. The deflection corresponding to this is found from (4) as follows:

$$d = \sqrt{\frac{300 \times .076}{8}} = 1.69 \text{ ft.} = 20.28 \text{ inches.}$$

A large allowance in deflection must therefore be made for such variations in temperature as are likely to be encountered in northern climates.

This matter of temperature is unfortunately not all that must be looked out for. We have taken care of the weight of the wire itself fully, but it is exposed to other and sometimes dangerous forces in the weight of the ice coating that is to be feared in winter and the strain of wind pressure on the wire either bare or ice-coated.

Taking up these in order, let us suppose the wire to become coated with ice to the thickness of half an inch, quite a possible contingency in severe winter storms. A layer of ice of this thickness would weigh 0.54 lb. per linear foot, thus loading the wire with more than its own weight. Assuming this load at the minimum temperature of $-5°$ for which the assumed deflection was 0.57 foot, the tension of the ice-loaded wire becomes from (1),

$$T = \frac{(100)^2 \times .94}{8 \times .57} = 2{,}051 \text{ lbs.}$$

This is dangerously large, far beyond the elastic limit of the wire, and more than likely to bring down weak joints.

And beyond this the wind pressure must be considered. This may be taken as acting at right angles to the weight of the wire and adding materially to the resulting total stress. The total pressure P on a wire is, per foot, approximately $P = .05\, p\, D$, where p is the normal pressure of the wind per square foot and D is the diameter of the wire in inches. p

varies from a few ounces per square foot in light breezes to 40 or 50 pounds in a hurricane.

Assuming 40 lbs. as the greatest pressure likely to be encountered, we can at once find its effect on the line under consideration. For our No. 00 wire

$$P = .05 \times 40 \times .364 = .728 \text{ lbs.}$$

This pressure is combined with the weight of the wire as a force acting at right angles, hence the resultant stress, which we may call W, is

$$W = \sqrt{w^2 + P^2} = \sqrt{(.4)^2 + (.728)^2} = .83.$$

This, from the example given, is obviously a dangerous strain on the wire. But the combination of even half the normal wind pressure just assumed with an ice-coated wire would be disastrous. Taking the ice as half an inch thick as before,

$$D = 1.36, P = .05 \times 20 \times 1.36 = 1.36,$$

and

$$W = \sqrt{(.94)^2 + (1.36)^2} = 1.65.$$

Substituting in (1)

$$T = \frac{(100)^2 \times 1.65}{8 \times .57} = 3,618 \text{ lbs.}$$

This is over the breaking weight of the wire, which must consequently give way, and would almost infallibly wreck the line in so doing. This means that the factor of safety of 4, assumed at the start, is too small for due security. It is sufficient for a moderate climate, where high winds are rare, but 5 is generally preferable, while 7 or 8 should be used in cold and exposed regions. It must be remembered that joints are weak points in the wire; a carefully soldered Western Union joint has only about 85 per cent. the strength of the wire.

The same process that served to take account of an ice coating, *i. e.*, adding the distributed load to the weight of the wire, can be readily applied to finding conditions of safety in the use of bearer wires carrying the conductor suspended from them.

An interesting corollary to these computations is finding the maximum length of span which can safely be used in an

emergency such as crossing a river or cañon. Suppose we use simply hard-drawn copper wire of the same size as before. Its ultimate tenacity is about 6,270 lbs. Using it with a factor of safety of 6, the permissible value of T becomes 1,045 lbs. W is as before 0.4 lb. and we will assume that for the purpose in hand the wires are spread and the deflection is permitted to be 10 feet. Now transposing (1) we have for the permissible length of span

$$L = \sqrt{\frac{8\,T\,d}{W}}. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Substituting the above values of the known quantities, we have

$$L = \sqrt{\frac{8 \times 1045 \times 10}{.4}} = 457 + \text{feet.}$$

In more extreme cases a bearer of steel cable may be used, of the highest available tenacity, and carrying the copper line wire to secure the requisite conductivity, or a steel or silicon bronze wire may be used alone: the conductivity being made up elsewhere in the line to the desired general average. The steel is rather the more reliable of the two, but is more likely to deteriorate through rusting. An ultimate tenacity of 150,000 lbs. per square inch is about the most that can be counted on in either material.

Now assuming No. 00 silicon bronze or its equivalent in steel cable and the same factor of safety as before, the working tension rises to 2,612 lbs., and allowing 20 feet deflection, the possible length of span is

$$L = \sqrt{\frac{8 \times 2612 \times 20}{.4}} = 1{,}022 + \text{feet.}$$

Spans of this length can be managed without any very elaborate terminal supports. When the line wires are heavy and numerous, or longer spans must be used, it may be necessary to use stout bearer cables, arranged like a rudimentary suspension bridge with a footpath, to facilitate inspection and care of the conductors. The expense of such a structure is sometimes justified by enabling one to avoid long and expensive detours. When a simple long span of conductors is used, the support of the ends and the proper insulation of the tense wires require care. A timber truss well guyed will

answer in most cases, and the strain may be distributed among several stout insulators. The conductors should always be in duplicate across such a span.

When bodies of water too wide for a suspended structure must be crossed, there is trouble ahead. In marshy shallows a timber trestle is perhaps the best way out of the difficulty, but in deeper water recourse must be had to cables.

Gutta percha is the most reliable insulation in such cases, and cables can be obtained that will stand 2,000 to 3,000 volts alternating current with a fair factor of safety. Above this pressure success is problematical. Near the ends of the line before the raising or after the reducing transformers, cables may be successfully used, but when the obstacle is in the middle of a long line the choice is between evils, reducing the pressure locally by an extra transformation or going the long way around. Either expedient is costly. It is almost needless to say that when cables are used they should be in duplicate.

POLES.

As a rule all aërial lines in this country are carried on wooden poles. Iron poles are used much for railroad work, and abroad considerably for miscellaneous work, including power transmission. They are, however, not to be recommended for high voltage transmission work, as they give altogether too good an opportunity for troublesome and dangerous grounds. The ordinary wooden cross arm is of very little value as an insulator at high voltages, particularly after it has weathered for some time and gets dirty. Its resistance in damp weather may amount to only two or three thousand ohms from end to end, and such a cross arm, while allowing severe leakage in case of more than one insulator on the same cross arm breaking, would permit a highly dangerous ground on an iron pole in case of a fault in a single insulator. An iron pole with iron cross arm is infinitely worse. Moreover, iron poles cost so much more than wooden ones that the difference in expense, capitalized, will generally much more than meet the depreciation of a properly built wooden pole line, even if the iron poles were to have an infinitely long life.

In the eastern and central parts of the United States white

Northern cedar, Northern pine, and chestnut are the most desirable woods for poles, in the order named. West of the Rocky Mountains redwood is rather a favorite and stands next to cedar in estimation. Abroad, Norway fir is highly valued.

For power transmission work the poles should be both long and strong—long to carry the wires well out of reach and often above other circuits; strong to stand the pressure of the often heavy wires and the wind. The poles should be straight and free from knots, of sound, live wood, and the bark should be peeled and the poles trimmed and shaved.

The following table gives the size and other characteristics of the poles most likely to be used on power transmission work. This is based on cedar poles, and the dimensions given are the minimum to be permitted in first-class line construction. Pine and redwood poles are of about the weight given, chestnut is nearly half again as heavy.

TOTAL LENGTH IN FEET.	DIAMETER AT TOP—INCHES.	DIAMETER 6' FROM BUTT, IN INCHES.	DEPTH OF SETTING.	APPROXIMATE WEIGHT, IN POUNDS.	NUMBER THAT CAN BE LOADED ON A PAIR OF CARS.
35	7	12½	5' 6"	650	90
40	7	13	6'	900	75
45	7½	14	6' 6"	1,000	65
50	7½	16	7'	1,300	50

It will be noted that poles of these lengths have generally to be carried on two cars, one being too short. Various preservative processes are used to increase the life of wooden poles. Of these "creosoting" is generally preferred. The process consists of stowing the poles in an air-tight iron retort, exhausting the air, and with it withdrawing the sap and moisture, treating with dry steam for several hours, and then forcing in the preservative fluid, often crude petroleum, under heavy hydraulic pressure.

When not specially treated, the poles should be coated heavily with pitch or tar on the portion to be buried and fairly

above the ground level. The whole pole may be similarly lightly coated, with advantage in point of durability.

The pole top is usually wedgeshaped or pyramidal, and this roof should be painted or tarred. Before the pole is erected the gains for the cross arms are cut and the cross arms themselves should be bolted in place. The upper cross arm centre should be 10 to 18 inches below the extreme apex of the pole and the lower cross arms 18 to 36 inches further down. In power transmission work employing heavy wires the spacing of the cross arms should be guided by the arrangement of the circuits, there being no standard practice.

The cross arms themselves are of wood having the same characteristics of strength and durability as the poles; hard yellow pine being rather a favorite. They are of course of such length as the work demands; in power work, generally from 4 to 8 feet. There are two sectional dimensions in common use, 4¼" × 3¼", and 4¾" × 3¾". The latter should be used for the longer cross arms and those carrying heavy cables or the like, while the former serves for 4' or 5' arms not heavily loaded. The cross arms are best secured in their gains by a strong iron bolt passing through both the pole and the cross arms in a hole bored to fit and set up hard with wide washers under head and nut. This construction makes a cleaner job than the practice of fastening the cross arm with two lag screws, and permits of easier changes and repairs. The bolt should be about three-quarters of an inch in diameter, and the gain is from 1" to 2" deep according to the size of the pole. Cross arms 6' long or more should be braced with diagonal iron straps.

In ordinary transmission circuits about 50 poles per mile should be used. The setting should be carefully done. The earth should not be disturbed more than enough to make easy room for the pole, and the earth and gravel filled in around the pole should be heavily tamped. When setting poles in soft ground it is sometimes impossible to give them stability enough merely by tamping, and the best procedure is to fill in concrete about the pole, using one part of Portland cement to two or three parts of sand and heavy gravel or broken stone.

The stresses to which a pole line is exposed may be classi-

fied as follows: 1. The direct weight of the wire and the downward component of the wire tension. 2. Bending moment due to the pull of the wires at turns in the line. 3. Wind pressure on poles and wires. 4. Wind pressure plus ice.

1. In power transmission lines built as has been indicated the crushing stress is completely negligible. The ultimate resistance against crushing amounts in the woods used for poles to at least 5,000 lbs. per square inch. The ordinary pole therefore has a factor of safety of several hundred, and the danger of crushing, even from tense and ice-laden wires, has no real existence.

2. Bending moment is more serious, since the forces acting have a long lever arm. The ultimate effect of this stress is to break the pole, generally near to the surface of the ground, by crushing the fibers on the side next the stress and pulling apart those on the other side. The pull or push necessary to break a round pole by bending is approximately

$$P = \frac{A\,S\,R}{4\,D}, \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where A is the area of the pole section at the ground, S the strength per unit area, R the radius at the ground, and D the distance between the ground and the centre of pressure.

For example, take a 40′ pole, 13″ in diameter at the ground. Taking $S = 7,500$ lbs. per square inch and the centre of pressure as 32′ above the ground, (6) becomes

$$P = \frac{132 \times 7,500 \times 6.5}{4 \times 12 \times 32} = 4,189 \text{ lbs.}$$

The factor of safety allowed should be approximately 5. Practically, poles at angles should always be guyed, like terminal poles. This is best done with a steel rope one-quarter to one-half an inch in diameter, taken from as near the centre of the stress on the pole top as the position of the circuits permits. The guy rope should extend downward at an angle of from 45° to 60° with the pole, directly back from the direction of the pull on the pole, and should be drawn taut and securely fastened to a tree or a firmly set post. Where there are three or four cross arms what is known as a *Y* guy is often used, consisting of a guy rope attached near the pole top and another

just below the cross arms. These divide the tension and are moored by a single guy rope in the ordinary manner. This arrangement is not commonly needed in transmission work save when the circuits are numerous or the strain exceptionally severe, and in any case great care should be taken to keep the guy wires well clear of the high voltage lines. Sometimes two or more light guys in different directions are valuable in securing a pole, when proper setting is very difficult, and may save expensive blasting.

The bending moment due to an angle is normally $2\,T\cos\frac{\alpha}{2}$ where T is the tension as already determined and α is the angle made between the wires at the turn. For the simple circuit of No. 00 wire already discussed and a turn with 120° between the wires, taking a factor of safety of 7 on the wire, the tension per wire is 507 lbs. The total pull for the two wires forming the circuit is then 2,028 lbs. $\times$ cos 60° $=$ 1,014 lbs., a pressure rather greater than would be permissible without guying.

3. The wind pressure on the wires has already been computed, and the same formula serves for figuring the pressure on the poles, using the mean diameter in inches, and for the total pressure multiplying by the feet of pole exposed. For example, assuming a pole 34′ out of ground, 7″ diameter at the top and 13″ at the ground, the average diameter is 10″, and for a storm giving a normal wind pressure of 40 lbs. per square foot,

$$P = .05 \times 40 \times 10 \times 34 = 680 \text{ lbs.}$$

This acts virtually at the middle point of the pole, hence it is equivalent to 340 lbs. at the pole top, to which must be added the pressure on the wire itself, which for the circuit in question amounts to about 145 lbs. more, making a total of 485 lbs. This is well within the safety limit, and would remain so even if there were half a dozen wires instead of two. As 40 lbs. per square foot is an extreme wind pressure, never met in most localities at all, it is safe to say that a well-set line of the poles assumed, loaded with any power transmission circuit likely to be met in practice, is perfectly secure so far as wind pressure alone is concerned.

4. The most dangerous stresses on an aërial line come from sleet storms that load the wires with ice, increasing the weight and the lateral thrust due to wind pressure. On rare occasions ice may be formed on wires to the depth of a couple of inches. Such a coating on a No. 00 wire would weigh about 5.9 lbs. per linear foot. The mere weight of this would produce a tension assuming $d = 2'$, and No. 00 wire as before,

$$T = \frac{(100)^2 \times 6.3}{8 \times 2} = 4{,}000 \text{ (very nearly)},$$

which is well above the tensile strength of the wire. Allowing a wind pressure of 20 lbs. per square foot, the pressure on a single span of 100 feet would be

$$P = .05 \times 20 \times 4 \times 100 = 400 \text{ lbs.}$$

Adding to this 170 lbs. pressure on the pole itself, the total for a single circuit of 2 wires would be 970 lbs. total thrust, which, while high, is not likely to carry down the pole. Even 6 No. 00 wires would give a total thrust of only 2,570 lbs., which is still below the ultimate strength of the pole. The pole line is therefore stronger than the wires. If a line is to stand such extreme stresses, which are far beyond really practical requirements, the only safe plan would be to string hard drawn wire, shorten the poles and increase the diameter, and guy frequently. As a matter of fact the insulators and their pins are quite sure to give way before the wires or poles under these extreme stresses, and in most transmission lines are the greatest source of anxiety.

The insulators themselves can be made strong enough to stand the greatest stresses to which they will be subjected, but it is not easy to so support them as to give ample strength without endangering the insulation. The ordinary wooden pin answers well if the circuits are not very heavy or likely to be weighted with ice.

By common consent locust is the material best suited for pins, which for general line work are about 12" long and 2" in extreme diameter at the shoulder, below which the pin is cylindrical and 1½" in diameter. This fits a hole bored in the cross arm and is secured by a nail driven through arm and pin. The top of the pin is threaded for the insulator to be used. Under extreme forces these pins are liable to break at the

shoulder; and for transmission circuits carrying very heavy wire, for long spans and for cases where special insulators demand extra long pins, a variation of this construction is desirable.

Iron or steel pins have been tried, but while they have ample strength they are an element of weakness in insulating very high voltages, tending to work and grind the interior of the insulator and furnishing an interior conductor which much enhances the danger of puncture.

A better device is to make a heavy pin with a base 2" or more square and clamp it to the cross arm with an offset iron strap the full depth of the cross arm.

In ordinary line work the pins are set 12" to 14" between centres. With heavy wires this distance may advantageously be increased to 18" to 24".

When the lines have to be transposed, as in long parallel alternating power circuits, this transposition involves some careful work, for the wires must be kept well clear of each other. Heavy strain pins clamped as described will generally answer the purpose and allow the transposition to be safely made. Such transposition should not be made at an angle or elsewhere where the tension on the insulators is unusually great.

A good example of line construction for heavy transmission work is found in the line recently constructed for the Niagara-Buffalo power circuit. Fig. 198 shows the pole head. The cedar poles, intended ultimately to carry 12 cables each of 350,000 c. m., are extra heavy, varying from 35 to 50 feet in length with tops 9" and 10" in diameter. The two main cross arms are of yellow pine, 12' long and 4" × 6" in section, fastened to the pole with long lag screws, and braced by an angle iron diagonal ¼" × 2½", bolted to the pole and to the bottom of the cross arm at each side. Each side of each arm is bored for three pins spaced 18" apart. The transmission is three-phase and one complete circuit is on each side of each cross arm. The cross arms themselves are 2' apart.

The pins and insulators, Fig. 199, are special, the pins being much heavier than usual and the insulators of dense porcelain formed in the usual double petticoat design. They have one peculiar feature: a gutter is formed on the external surface,

leading to diametrically opposite lips so placed as to shed dripping water clear of the cross arm, thus lessening the danger of ice formations. Each of the main circuits is designed to transmit 5,000 HP. A short cross arm below the others carries a private telephone line. The right of way is in part owned by the operating company and fenced in, and in part along the Erie canal. The line is elaborately transposed every five poles to annul induction.

This line is admirably constructed, but it is a grave question

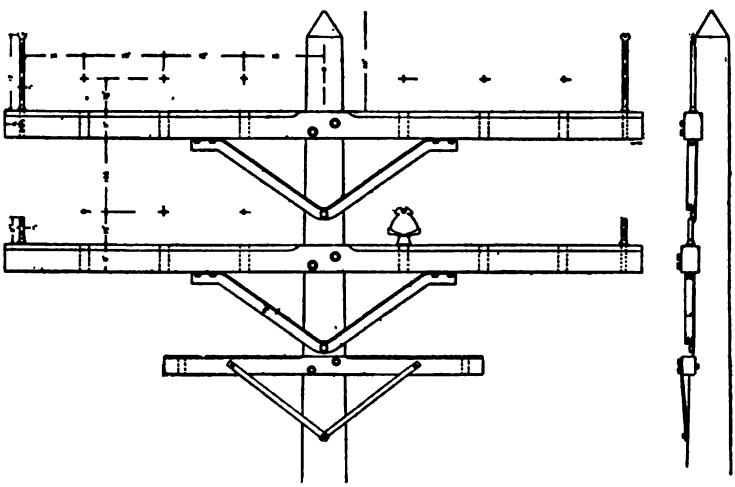


FIG. 198.

whether all the circuits should be carried on a single pole line on account of the difficulty of executing repairs, and the insulators are rather closer to the cross arms than seems safe in view of the climate and the high voltage to be employed.

Sleet is greatly to be feared on such lines, for although ice is a very fair insulator, at 10,000 or 20,000 volts it is not difficult to start enough leakage to break down the insulation and very likely burn off a cross arm. In one case that has come to the author's notice a tree trunk 16" in diameter was burned entirely off by a wire carrying a 5,000 volt alternating current in the course of less than a day.

Security is absolutely necessary in a power transmission line, so that the construction must be calculated and executed with

particular care. There are many useful precautions that can be taken, such as guard irons to prevent wires slipping from the cross arms when an insulator breaks, specially braced poles at short intervals to relieve longitudinal strains, local cut-out stations to facilitate the execution of repairs, and so forth. Whatever the general construction, two things in particular

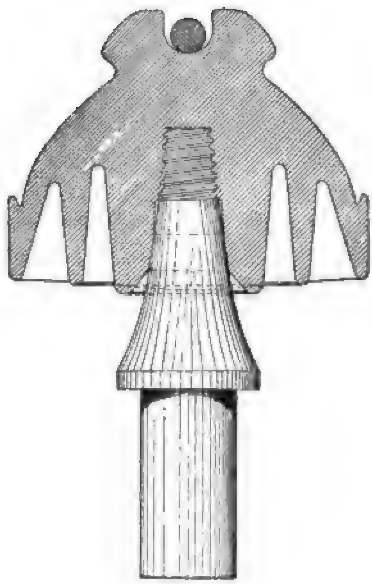


FIG. 199.

must be kept constantly in mind: The insulation of the line must be kept up, and must be constantly watched and tested.

Ordinary methods of testing insulation are nearly useless on high voltage lines, since a line may show practically perfect insulation with a testing battery and be practically grounded when used at 10,000 volts. Experience shows that high voltage lines must quite generally be considered as grounded, even aside from the apparent grounding due to capacity. On high voltage systems means should be provided for testing the insulation at or near the working voltage. This involves some trouble, but is well worth it, since, if the insulation is faulty, it is apt to go rapidly from bad to worse and to end in an interruption of service. It is not a difficult matter to construct a high

resistance bridge, using tubes of Hittorf's cadmium iodide solution, and whether the bridge or any other of the familiar methods of measuring very high resistances be used, it is not a hard task to make a testing battery even for 10,000 volts, using storage cells made out of homeopathic pill vials and U-shaped bits of lead wire, or to test with alternating current.

Lines should be tested as often as the opportunity offers, and any signs of weakness in the insulation followed up closely. High voltage lines are likely to develop faults very quickly indeed if there is incipient weakness in the insulation.

Another matter of most grave importance is the installation and maintenance of proper defences against the effects of lightning. Now and then a plant may be located so that it is practically safe from lightning, but in most localities thunderstorms are not rare during a portion of the year and may be the source of frequent disaster.

There are two distinct classes of lightning strokes which may affect aërial circuits. The first is a direct stroke from the flash itself, taking the line as the last minute portion of its terrific leap to earth. The other is secondary, being the induced current due to the enormous energy of the primary discharge quite apart from the line and perhaps striking from cloud to cloud. When these tremendous electrostatic stresses suddenly change by a discharge, the induced discharges from conductors may be very formidable.

Akin to this phenomenon are the sometimes very great potential differences between line and earth produced by the readjustment of the charges on earth and clouds raising the potential of the insulated line. The line and earth will normally be at about the same potential with respect to a heavily charged cloud, but when the clouds and earth are mutually discharged the insulated line may assume a very high potential with respect to the earth and produce a violent disruptive discharge, quite akin to lightning. This kind of static discharge may be produced when there is no storm and no indication of anything unusual in the atmospheric conditions. It may be trivial, only enough to give small sparks or a smart shock, or it may be highly dangerous and very serious in its results.

The direct lightning stroke is at once the most formidable

and the least common of these forms. It may strike the line fairly or merely give it a branch discharge of greater or less magnitude. Next in frequency and severity comes the secondary lightning flash, which is far more common and is the variety most generally observed during thunderstorms. The static

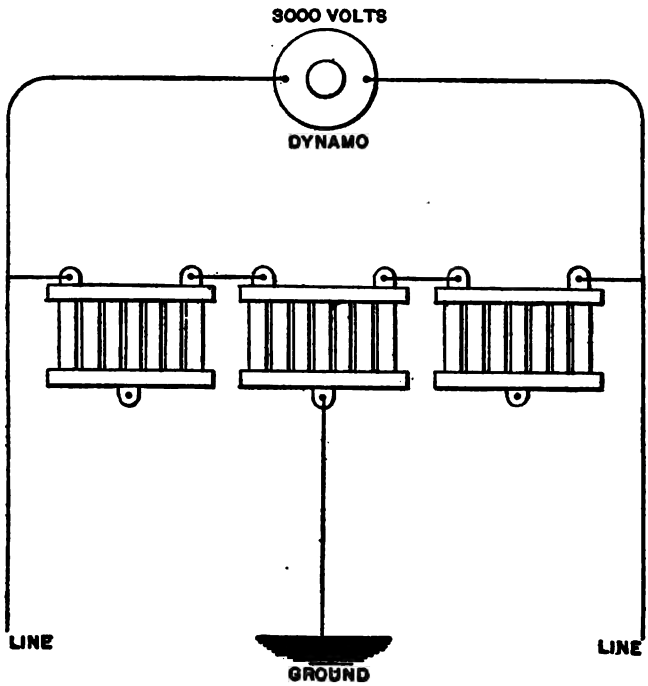


FIG. 200.

flashes last mentioned are somewhat difficult to distinguish from the secondary flashes and are probably even more common. They make up the bulk of the line disturbances in clear weather or coincident with distant storms, and as a class are less to be feared than the direct and secondary strokes. Lightning arresters, so called, are in the main short spark gaps between the line and a grounded conductor, furnishing the discharge an easier path to ground than going *via* the power-house machinery or an insulator and pole. In connection with this spark gap is some means for preventing the dynamo

current from following in the wake of the lightning and producing a short circuit. This result is accomplished by various means, probably the best being the Wurts and the Thomson devices. The former is shown diagrammatically in Fig. 200, where three of the arrester units are put in series across the high voltage line. Each consists of seven milled cylinders of the so-called "non-arcing metal" set one-sixty-fourth inch apart, thus furnishing six spark gaps in series. The lightning jumps these gaps, but the following arc is choked and broken by the whiff of non-conducting oxide thrown off in its passage. On continuous current, the arc is likely to be maintained.

The Thomson device is shown in its simplest form in Fig. 201. It consists merely of a spark gap or a series of gaps, in

FIG. 201.

the field of a powerful magnet energized by the current from the generator with which it is in series. The arc is blown out instantly by the magnetic field. The cut shows the form used for high voltage arc circuits, provided with only a single spark gap, formed by a pair of metal horns to the tips of which the arc is repelled and broken. With alternating currents it is less easy to get a powerful blowing out effect, and several gaps are placed in series in the field of a laminated magnet. The inductance of the magnet of course itself tends to throw a lightning discharge to earth.

Either of these devices will prevent the maintenance of an arc, but the real difficulty is to prevent the lightning damaging the line or apparatus in spite of the alluring earth connections. So far as apparatus is concerned it is probably possible to secure adequate protection, but it is very doubtful whether any contrivance will suffice to protect the line insulation from the results of a direct lightning stroke. At the station the best plan is to put several arresters in the line, each followed by an inductance coil. As lightning is an enormously rapid discharge it will jump any reasonable gap to earth in preference to passing the inductance, which, for the frequency of the dynamo current, is of trivial amount. The use of inductances for this purpose has long been known, but in the development of long high voltage lines it has acquired greatly increased importance. Fig. 202 shows in diagram inductance coils and Wurts arresters grouped for the protection of the station. Mr. Wurts, who has made an exhaustive study of the subject of protection against lightning, advises the frequent installation of such banks of arresters along the line.

The use of such a series of arresters is good practice, for it is very doubtful whether any single arrester and inductance coil could so effectively shunt the lightning to earth as to obviate danger of a branch discharge passing the device and damaging the apparatus. In fact, in a group like Fig. 202, Mr. Wurts has very often found the middle spark gaps doing the work, showing the need of several arresters in series.

Inductance coils must, however, be used with caution on an alternating circuit, since they add to a general inductance already too much in evidence and, if sufficient to deflect lightning across the arresters to earth, will, when used frequently, seriously increase the line inductance.

One of the commonest devices to lessen the danger from lightning, is a line, usually of barbed fence wire, carried on the pole top and grounded at frequent intervals. In the Niagara Buffalo circuit shown in Fig. 198, such lines, grounded at every fifth pole, are to be carried on the guard irons at each end of the upper cross arm.

In certain cases these guard lines have worked well; elsewhere they have proved totally useless. A line of barbed wire strung above the main line certainly has a considerable tend-

ency to keep the atmospheric potential equalized in its immediate neighborhood, and thus may check minor static phenomena. It also may catch certain branch discharges from a nearby lightning stroke, and ameliorate minor secondary discharges, but there is little reason to expect much more than this.

The guard line would have to be carried well above the other wires to be of much use as a lightning rod in case of a

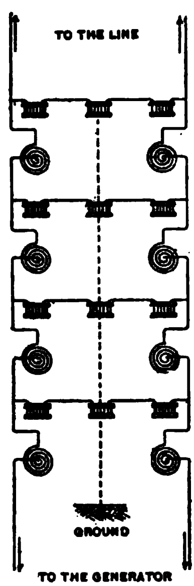


FIG. 202.

direct stroke, and is powerless to prevent secondary strokes or static discharges between wire and earth. In regions where the danger of lightning is not very great and the discharges mostly weak such a guard line well grounded is of material assistance, but where protection is needed most, such a line must be regarded merely as a precaution of possible utility, but of little value unless reinforced by special apparatus.

So far as the station is concerned the best procedure is to

install a bank of lightning arresters, coupled with inductance coils as already described if the arresters do not have sufficient inductance in themselves, preferably putting the arresters outside the station and always grounding them thoroughly. When on polyphase circuits, the arresters on each phase should be provided with separate ground wires, grounded far enough apart to have between them resistance sufficient to prevent a destructive short circuit if the phases are connected. A common ground wire may lead to so tremendous a short circuit as to demolish the arresters in spite of all precautions. This station protection must be kept in the best of order, for on long power circuits it is no very unusual thing to see the arresters flash several hundred times in a single storm or for them to be almost continuously in action for some minutes at a time, and with all this use the arresters must not break down.

As regards the line there is no complete protection available, and with the utmost precautions there is still a chance for a lightning discharge sufficient to break down the insulation of a high voltage line. About the most that can be done is to use a guard line, grounded say every thousand feet, and to protect danger points with special lightning arresters like those at the station. Such danger points may be found on high ridges and other places where observation shows lightning strokes to be frequent, and particularly the terminals of any underground or submarine cables, banks of transformers and other apparatus along the line. If the line is in sections with section boxes for testing, cutting out, and similar work at each section end, these are the places for lightning arresters. The author most emphatically does not believe in the general scattering of lightning arresters along the line on every pole or every few poles. If the line is at 10,000 or more volts the arresters are likely to operate on very small provocation, and numerous arresters mean a great number of grounds unless they are kept in the best of order. Therefore the arresters must be put where they can have frequent examination and testing, which is impracticable if they are scattered promiscuously along the line.

Barring cyclones and earthquakes, an aërial line, carefully designed and constructed, is exceedingly durable and reliable.

If the poles are creosoted or similarly treated they should last easily twenty or twenty-five years, and the rest of the structure is nearly as durable, while bare wire does not deteriorate sensibly.

A poorly set line of cheap material, on the other hand, may be unserviceable in less than half this time. Here, as everywhere else, good work pays.

CHAPTER XII.

CENTRES OF DISTRIBUTION.

In many cases of power transmission the primary object is the supply of power and light in various proportions throughout a more or less extended region. Therefore the question of methods of distributing electric energy, after it has been received from the transmission line, must often be carefully considered. The subject may conveniently be treated in three divisions: First, distribution direct from the transmission circuit without the use of special reducing transformers or sub-stations. Second, distribution from scattered sub-stations. Third, distribution from a main reducing station. These divisions do not have rigid boundaries and often overlap, but they involve three quite diverse sets of conditions.

Into the class first mentioned fall all the ordinary electrical installations wherein the power station is separated from its load by a transmission line. This line is usually of moderate length, for otherwise the voltage used would need to be reduced for the working circuit, and the region supplied is generally a town or city of moderate size. Such cases are common enough and generally arise from the existence of a convenient water power half a dozen miles, more or less, from a town that needs light and power, or that has already a central station which from motives of economy it is desirable to operate by water power. The power is therefore developed and new distribution lines are erected, or the old ones reorganized. The whole condition of things is closely similar to ordinary central station practice, save that the load is all at a considerable distance from the station. Only the use of alternating current need be considered, since this current alone is practically employed for general purposes at distances above a mile or two.

The rudimentary map, Fig. 203, gives a case typical of many. The power station is at *A*, with a line across country to the

town which is to be supplied with light and power. The distance to the town, *A B*, is perhaps five miles. Now the problem is to distribute the energy derived from *A* over the town in the best and most economical way. Since much lighting as well as motor service is to be done, good regulation is essential, while abundance of water makes small variations in efficiency of little moment. The town is scattered, with a main business street, *C*, running lengthwise through it.

There is here little object in a sub-station, for the distances are too great for convenient distribution at low voltage, and the short transmission makes it desirable to avoid raising and reducing transformers. The choice of a system is the first consideration. This is not a question of such vital importance as the average salesman hastens to proclaim. The skillful organization of the installation will make much more differ-

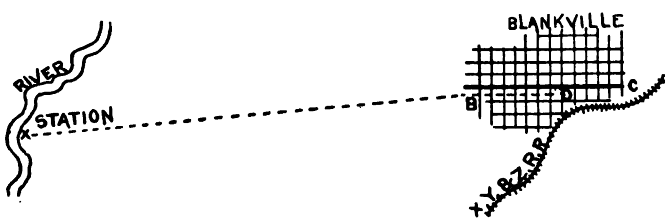


FIG. 203.

ence in the general success of the plant, than the particular species of apparatus used. This should, however, be determined with due regard to the local conditions.

Any alternating system except plain monophase can be made to do excellent service, and monophase is inapplicable only in default of suitable small motors, which are not at the present time available in this country, although they are even now in experimental service and may soon be forthcoming. Something depends on the character and amount of the motor service. If it be very considerable and in all sorts of service, general experience both in this country and abroad indicates some advantage in triphase apparatus. This advantage, however, depends more on the ease and economy with which a triphase distribution can be carried out, when motors and lights are to be served in the

same territory, than on any intrinsic advantages in the motors. When made with equal care and skill all polyphase motors are substantially alike in their properties. Details of the various systems of distribution will be given in treating sub-station work. Where the motor service consists of a few large units, even the monophase system with synchronous motors is entirely practicable. Diphase, monocyclic, and triphase systems can be advantageously applied to any case that is likely to arise; and which one will best fit it is a matter that only a trained engineer with full knowledge of the local conditions can properly decide.

Of far more importance are the general methods employed in carrying out the electrical distribution, and these are applicable with equal force to any sort of alternating system.

First in importance is the maintenance of a uniform voltage on the primary service lines. This voltage should as far as possible be the same at every transformer and should be constant, save as it may be raised to compensate for the loss in the secondaries.

The first step toward obtaining this uniformity is to assume a fictitious centre of distribution as at *D*, Fig. 203. This should be chosen at or near the centre of load, generally in the business centre of the city. If the office of the operating company is conveniently situated it should be used as a habitation for the centre of distribution, at which supplies can be kept and measurements made. *D* is taken as the termination of the transmission line proper and acts in the capacity of a central station toward the primary service wire. As a preliminary toward a more exact regulation, there must be means for keeping the voltage at this point *D* up to the normal under all conditions of load. The most obvious suggestion is overcompounding the generators for constant voltage at *D*, and this is often advisable, though it must be remembered that compound winding is by no means the only and not always the best means of securing constant voltage at a point distant from the generator.

When the circuit is nearly non-inductive, and the current therefore very nearly in phase with the E. M. F., compounding works admirably, and so is readily applicable to cases

where lighting is the main work to be done or where synchronous motors keep up the power factor of the system.

If, however, the load is largely of induction motors, running at all sorts of loads, or is otherwise of strongly inductive character, compound winding alone will not suffice to keep constant voltage at the point *D*. It will fail in proportion to the amount of compounding necessary to be employed and for two reasons: first, because of the direct effect of the lagging current on the excitation necessary; and second, because, as has already been pointed out in Chapter VI., the lagging in phase of the current disturbs the functions of the commutator. It is, therefore, desirable to bring "pressure wires" back from *D* to show at the station exactly the condition of things at the load, so that the voltage may be maintained by hand regulation, if necessary. This is of course a temporary expedient with a compound-wound machine, but it may avert frequent bad service. The pressure wires may come either from the primary circuit at the centre of distribution or from some point of the secondary system which is chosen to represent average conditions of load. The latter is the preferable method, if there is a fairly complete system of secondary mains. The pressure wires may be taken as a guide for close hand regulation or may operate some form of automatic control of the field rheostat. Neither hand nor automatic control is very satisfactory, if the generator requires great change of excitation under change of load. For the class of power transmission under consideration it is therefore better to use a generator of moderate inductance and armature reaction, whether it be compounded or otherwise regulated.

Granted now that means are taken to regulate the voltage at *D* as it would be regulated if the generator were at that point, the distribution problem is the same as that in an ordinary central station. Most alternating stations, however, are far from well organized in this respect. Nothing is at present commoner than to find an alternating station which receives pay for not more than one-half of the energy delivered to the lines, and sometimes this low figure falls to one-third or even a quarter. This unhappy state of things is due mainly to badly planned secondary circuits and to the indiscriminate use and abuse of small transformers. The alternating current

transformer is a marvellously efficient and trustworthy piece of apparatus, and, perhaps in part for this very reason, it has been often the victim of wholesale misuse. Without going in detail into the case of sub-station *vs.* house-to-house distribution, it is sufficient to say that the essential thing for efficiency is to keep the transformers in use well loaded and hence at their best efficiency, and that for this purpose a few large transformers are, on the whole, better than many small ones. The reason for this may be best shown by taking the following practical example:

A given region requires, let us say, 250 incandescent lamps or thereabouts, together with fan motors and perhaps an occa-

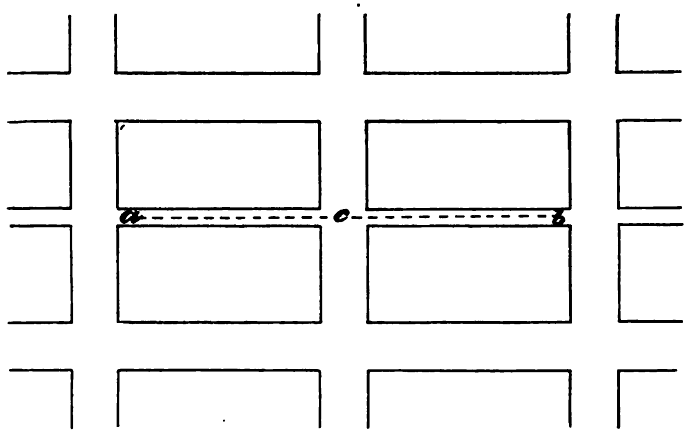


FIG. 204.

sional larger one. These are distributed among a score of customers scattered over a couple of blocks, Fig. 204. The blocks are say 200 feet long, with alleys cutting them in two. Now these customers may be supplied from individual transformers, or all may be supplied from one transformer. In either case the lines should be carried in the alley. In the former case 20 transformers would be connected to service wires attached to the primary service main *a b*. These transformers would average say 12 lights capacity each (600 watts). In the latter case *a b* would be a secondary main supplied from a single transformer of 12,000 watts capacity. Now assuming a load such as would be met in ordinary prac-

tice, let us examine the transformer losses in each case. The day may conveniently be divided into three periods in considering load: 7 A. M. to 5 P. M. forms the day load of motors and a few lights; 5 P. M. to 12 night, the evening load; and 12 to 7 A. M., the morning load. During the first period we may assume 15 transformers to be quite unloaded, 2 to be three-quarters loaded on motor work except during the noon hour, and 3 transformers to be one-quarter loaded on day lights.

During the second period we will assume the motors to be

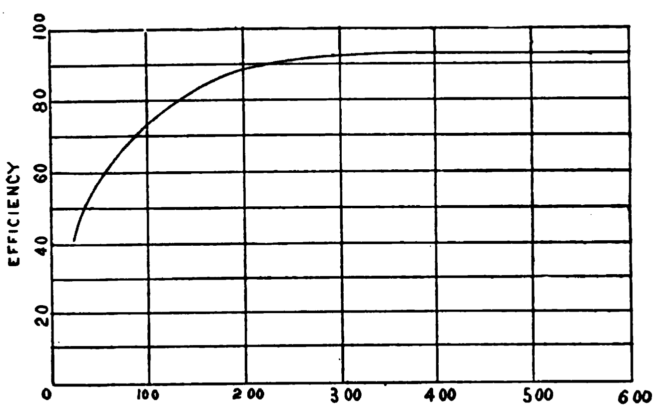


FIG. 205.

off, 8 transformers to be three-quarters loaded on the average from 5 until 7 P. M., and the rest one-quarter loaded from 5 until midnight.

For the third period it is safe to assume 15 transformers to be unloaded and the other 5 one-sixth loaded from midnight until 7.

Now the efficiency curve of a 500 or 600 watt transformer at various loads is approximately as shown in Fig. 205, derived from a consideration of several transformers of different makes. The constant loss, when the transformer is run unloaded, is about 30 watts.

On the above assumptions and knowing the efficiency of the transformer at various loads, it is easy to calculate for each period the total energy supplied and the transformer output

which is delivered and paid for. The result of this calculation is as follows:

	1st Period.	2d Period.	3d Period.	Total.
Energy Supplied in Watt Hours,	18,480	20,420	10,050	48,950
Energy Delivered " "	10,450	17,700	3,500	31,650

Therefore barely six-tenths of the energy supplied to the transformers is delivered by them to the consumers. And this is a condition of things more favorable than is usually found in stations of moderate size using, as most of them do, small transformers.

The other method of distribution is to use a single large transformer in place of the small ones and distribute to all the district by secondary mains.

Now the efficiency of a 10–12 KW transformer is very closely that shown in Fig. 206. Moreover the energy consumed when running without load is hardly more than 150 watts, so that the transformer, when absolutely unloaded, wastes only one-fifth of the energy wasted by the small transformers of the same total capacity. Taking the output for the same periods as before, a much better result is reached, as follows:

	1st Period.	2d Period.	3d Period.	Total.
Energy Supplied, Watt Hours,	11,800	19,660	5,830	37,290
Energy Delivered, " "	10,450	17,700	3,500	31,650

With the single large transformer more than 80 per cent. of the energy supplied to it is delivered on the customers' circuits. This means that for a given amount of energy supplied from the station one-third more revenue will be obtained if the distribution be accomplished by a large transformer as against quite small ones. Such a difference is important, even in a plant driven by cheap water power. Besides, for a given amount of energy delivered to the customers, high plant efficiency means smaller first cost of plant. With distribution by secondary mains not only will smaller dynamos at the power station suffice for the work, but the cost of the transformer capacity necessary is enormously reduced. In the house-to-house distribution it is quite possible for any transformer to be loaded with all the lights connected to it. When twenty customers are supplied from a single transformer the

chance of such an occurrence is almost *nil.* In the hypothetical case just discussed certain of the transformers would be called on for full output almost daily, while all of them would be subject to such a demand. The largest total regular output, however, would be not much over one-half the aggregate transformer capacity. So, instead of using a 12 KW trans-

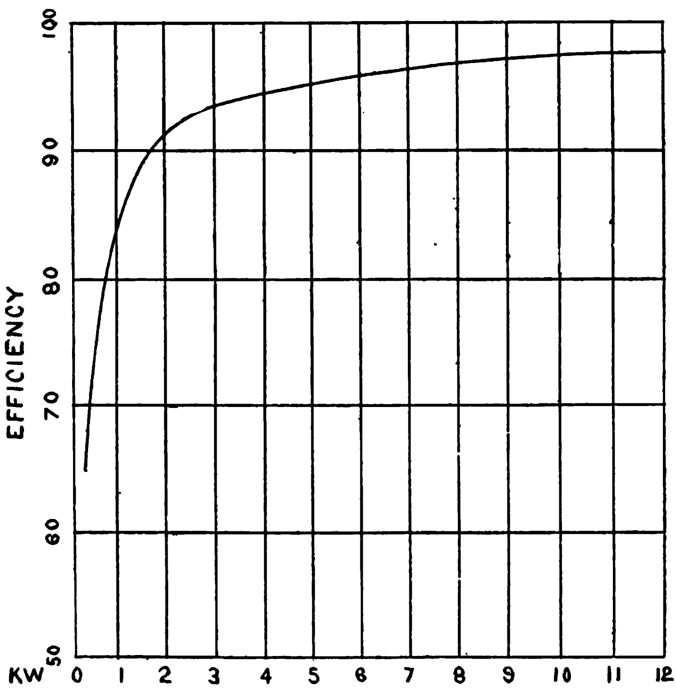


FIG. 206.

former to replace 20 small ones, in reality a smaller one, say one of 10 KW, would be ample.

In point of cost the single transformer would have the advantage by not less than $250, enough to much more than pay for the secondary mains. In regulation, too, the single transformer has the advantage, for the load is less liable to sudden fluctuations, and the transformer itself regulates more closely.

In practice it is best to go a step further than shown in Fig. 204 and connect the secondary mains at *a* and *b* to the next

section of secondary just across the street, and also *c* with the main in the next alley, so as to form, at least in the region of dense load, a complete secondary network. Thus each transformer can help out its neighbor, in case of need. The secondary mains should, in so far as is practicable, be designed for the same loss of voltage, and the compounding and other regulation applied to the generator should be arranged to compensate for the loss of voltage in the transformers, and to hold the voltage as steady as possible in their secondary mains. The perfection of such regulating arrangements depends of course on the uniformity of the distribution of load, but with a little tact in arranging the circuits variations in voltage at the lamps can often be kept within 2 per cent. of the normal pressure. In large systems, as will be presently shown, even better work can be done.

An essential point in the use of secondary mains is the employment of fairly high voltage. The general law, that the amount of copper necessary in a given distribution varies inversely as the square of the voltage, applies here with great force.

In the early stages of alternating work, when small transformers were nearly always used and regulation was generally bad, the favorite voltage for incandescent lamps was about 50 volts. The main reason for continuing this practice was the fact that it is not difficult to make a 50 volt lamp that will stand much abuse in the way of varying voltage. With good regulation this pressure can now be more than doubled with equal security from breakage and great advantage to the distributing system. Not less than 100 volts should be used, and a pressure of 115 to 120 volts is better, as it gives equally good service with a quarter less weight of copper. From the present outlook even higher voltage is becoming practicable.

It is not always advisable to do all the work of distribution by secondary mains. In districts where the service is scattered a few small transformers of various sizes can be very advantageously used, but should be generally employed as a temporary expedient only, and shifted to another field of usefulness when the service grows heavy enough or stable enough to justify installing secondary mains.

Recurring now to Fig. 203, we have found that the best pro-

cedure is to use an alternating system, compounded or otherwise regulated so as to hold the voltage as nearly as possible constant at the secondary terminals of the transformers. These should be large enough to do all the work within a distance of 200 feet more or less and should feed secondary mains at a pressure of say 115 volts. When these mains are more than usually long it is best not to feed current directly into them but to employ feeders connecting for instance *c*, Fig. 204, with points midway between *c* and *a*, and *c* and *b*, respectively. Neighboring secondaries may often be interconnected with great advantage.

As to the primary distribution we have assumed a centre at *D*, Fig. 203. From this point feeders should extend to primary mains connecting the transformers more or less completely, preserving nearly equal drop in voltage from *D* to each transformer. The degree of elaboration in this primary network is a matter to be determined by local conditions. If, for example, the plant is of rather small size and the drop from *B* to *C*, Fig. 203, is not above 1 or 2 per cent., the transformers may be connected to short branch lines crossing *B D C* at various points, without any further complications, or the main line may be branched at *B*, each branch having short cross feeders, while with other distributions of load the primary lines may be quite completely netted, with regular feeders from *D*.

The motor service may often require special treatment. It sometimes happens that it is best to feed large single motors or groups of motors from special transformers, which will generally be large enough to avoid the objections adduced against a general house-to-house transformer system. Such special transformers avoid throwing a large and varying load on the secondary lighting mains during the hours of "lap-load" when it might be objectionable, and thereby avoid needlessly heavy mains.

It must be remembered that Ohm's law is a very stubborn fact. Any apparatus that takes a large and variable current is liable to interfere with regulation. There is no such thing as a motor either for continuous or alternating currents which will not affect the lighting service. The nearest approach to such a motor is obtained by arranging the distributing system

so that the largest current taken by the motor will be insufficient noticeably to disturb the regulation of the lamps.

This means that care should be taken, in arranging the distribution, to avoid overloading the lighting mains with motors. It is an easy matter to determine the effect of the motor current by calculation if the current is continuous, and by experiment or calculation for alternating current. In the latter case the easiest way is to connect the motor with any convenient main and put on load with a brake—even a plank held against the pulley will do. Put an ammeter in circuit, and if at the rated amperage of the motor the fall in volts at the transformer is enough to endanger regulation, the motor should be put on transformers of its own. Generally the likelihood of trouble can be judged from the size of the motor and the load on the mains, without experiment. One of the advantages of regulation by secondary pressure wires is easier handling of an inductive load of which compounding generally alone takes no account.

One of the nice questions to be decided, in such a plant as is under discussion, is arc lighting. The alternating arc lamp is, all things considered, less generally satisfactory than the continuous current variety. It needs somewhat greater care and far better carbons. Fine, rather soft, cored carbons, costing at least twice as much as carbons for continuous current series lamps, are absolutely necessary for good service. In many cases the best plan is to install a regular continuous current system for the bulk of the arc lighting, using alternating lamps only when convenient. The alternating lamps, are, however, capable of giving good service when carefully looked after, and are likely to be used more and more as their care becomes better understood. Some humming must always be expected from them, varying from a scarcely audible note when the best carbons are used and the lamp nicely adjusted, to a loud and annoying one with poor carbons or improper adjustment.

The general principles of distribution laid down hold whatever alternating system is used. Polyphase and other modified alternating systems require special treatment in the details of distribution, but not in the broad methods employed.

Motor service should generally be cultivated as a desirable source of profit and an excellent way of raising the plant

efficiency. A motor load, if of numerous units or a few steadily loaded ones, is remarkably uniform. Fig. 207 shows the load line of a three-phase power transmission plant. The motor load consisted of about fifty induction motors of various makes, aggregating nearly 350 rated HP. The curve shows the primary amperes in one leg of the circuit

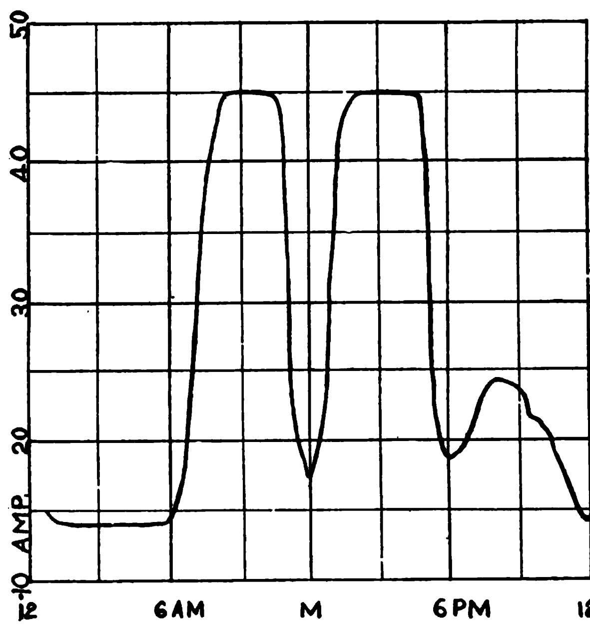


FIG. 207.

throughout the twenty-four hours. It was taken on a day in early August when the lamp load was very light and reached its maximum as late as 8 P. M. The motor load, save for the sharp decline during the noon hours, was very steady, although there were frequent variations through a range of a few amperes, too brief to appear on the diagram. In this case there is no "lap load." The distribution was, as far as possible, from secondary mains, and even in winter when the lap load is prominent, although the motors still require the major part of the output, the regulation of the system is admirable.

Thus even a heavy motor load gives very little trouble with a properly designed system of distribution and judicious handling. Now and then a system is installed for motor service only or with special motor circuits. In this case it should be remembered that there is no need for any close uniformity of voltage throughout the system and that to attempt it means waste of time and money. The circuits can be laid out with reference to the desired efficiency alone, for in most cases even 10 per cent. variation in voltage between one motor and another is of little consequence.

The distribution of power from scattered sub-stations fed by a common line involves some of the most intricate and puzzling problems to be found in power transmission. Such distributions generally arise from an attempt to supply from a common power plant energy for divers purposes to several separate towns or regions, having different requirements. In the main such plants require special treatment in order to secure decent service. A great variety of cases may arise, almost every plant having peculiarities of its own, but in general they will fall into one of the three following categories:

1. Radial distribution from a centrally located station.
2. Radiating distribution from an eccentric station.
3. Linear distribution.

1. The first-mentioned class consists of those plants which supply from a single station power to different localities lying in different directions, and generally at different distances. Fig. 208 shows the character of the conditions thus met. *A* is a generating station, the position of which may be determined by various reasons—the existence of a valuable water power being the commonest; *B*, *C*, *D*, *E*, *F*, are the various points to be supplied with power. They may be at any distances, and of any sizes or natures. Usually the greatest distance involved will not be coupled with the greatest load, and the situation is otherwise inconvenient. If all the loads were large, the simplest procedure would be to install one or more generators for each circuit and operate them independently. Or if by good luck two or more load points were of similar size, distance, and character, they would naturally be operated as if they were one.

To consider methods of operation more in detail, imagine a

system consisting of the station *A*, a load at *B* consisting of 150 KW in lights and motors, largely the latter, distant 3 miles ; and a load at *E*, 6 miles away, of 250 KW, mostly incandescent lamps. At both *B* and *E*, it would be desirable to distribute at the voltage of transmission without a general reducing station. In such a plant it might be possible to

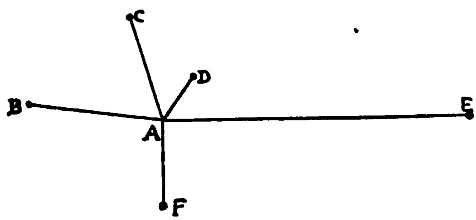


FIG. 208.

operate *B* and *E* from separate generators, compounding them or using the regulating methods already described. But if day lighting at *E* is to be attempted, it would be necessary either to run one dynamo all day at a trivial load or to throw this day work in on the other circuit and take the voltage as it chanced to come.

With the ordinary amount of loss in the line *A B*, the result would be decidedly bad regulation at *E*; with only motors at *B* or *E* the case would be very simple ; the station would be regulated with reference to the lighting load alone, but with lights at both places there must be good regulation at both. During the day at least it would be desirable to work both lines from the same generator. The first step in this direction would be to install at *A* a hand regulator to control the line *A E*. This might be such a device as that described on p. 467, or even a choking coil of variable inductance and sufficient range of action to prevent the generator, in compounding for *B*, from causing undue variations at *E*. As already pointed out a motor load is fairly steady except at certain times, so that the regulator would require little attention save in the early morning and at noon. Before the motor load fell off in the afternoon it would probably be desirable to start a separate dynamo for *E*.

In operating both lines regularly from the same generators hand regulation on at least one of them would become

necessary; on which one is a matter of relative convenience. If the distances *A B*, *A E* were much smaller, not more than two or three miles, it might be feasible to install both lines for small and equal drop—not over 2 per cent.—so that, if the dynamo were compounded for an equal amount, the possible variations of voltage would be trifling. Such a plan cannot, however, give really good regulation over any save very short distances without inordinate expense for copper. This sort of regulation by general average has been tried too often already, and is quite out of place in serious power transmission work.

If *A E* were 10 or 15 miles long the manner of operation would become a still more troublesome question. Raising and reducing transformers would generally be used, and the best plan would probably be to install a pressure regulator in connection with the raising bank of transformers, and let the shorter line be taken care of by the compounding of the generator or by a pressure regulator of its own. The latter procedure is somewhat preferable. For if the drop in the lines be 5 or 10 per cent. and the loads variable, the work of regulation will be lessened by compounding the generator, if at all, for constant potential at its own terminals. The range of the hand regulation is thus lessened since there is no attempt at over compounding; and two regulators requiring occasional adjustment are easier to handle than one which requires continual juggling to produce indifferent results.

In certain cases of heavy load there may be a regular sub-station at *B* or at *E*, the distribution at the other point being direct. Then the regulation question is better transferred to the sub-station, the generator being regulated for the loss in the other line which, as its load will usually be relatively small, should have a comparatively small drop.

The most troublesome case that can arise is when power is to be furnished to a street railway at *B* or *E*, in addition to a general lighting and motor service. A railway load is so violently variable that it cannot be operated in direct connection with an incandescent service unless this latter with the general motor load is so great as to quite dwarf the variations of railway load. Frequently, therefore, a separate generator should be devoted to the railway work. In case this cannot be done without great inconvenience, it may become neces-

sary to install a sub-station at which the lighting circuits can be regulated either by hand or automatically.

Suppose now that the problem is complicated by the addition of loads at *C*, *D*, and *F*. These lines will be treated by the same general principles as the first two. To begin with, any line operating motors alone can be worked direct from the generator. Even if all the loads be mixed in character, two or more can often be found which through similarity of conditions can be worked together in parallel, either by a common regulator or by compounding the generator. The others should be treated as already indicated. At the worst it might be necessary to install a regulator for each line. This is not really so burdensome as might be supposed, since several of the regulators will usually require infrequent attention, so that one man can manipulate the whole set. This line of action is similar to that followed in most large

FIG. 209.

central stations, where feeder regulation, although rather a nuisance, is successfully accomplished without any particular difficulty.

Pressure wires from each load point are desirable, though, if the load is such that the inductive drop is small or quite steady, the regulator can be easily adjusted in accordance with the amperes on the line.

In the transmission and distribution of power from an eccentric station, the difficulties are many unless recourse be had to a regular sub-station. Fig. 209 shows a typical situation. Here *A* is the generating station and *B*, *C*, *D*, *E*, *F*, are the load points. If the distance from *A* to the nearest load is great enough to require raising and reducing transformers it is generally best to install a reducing sub-station worked like the central station *A*, Fig. 208. Sometimes, however, it is only half a dozen miles or so from *A* to the

group of load points. The case is similar to that discussed in the first part of this chapter, save that the load is in several distinct localities instead of being generally distributed. From this difference the complication arises. A certain proportion of cases cân be treated readily, however, by choosing a point *G* near the centre of load and then running the lines *G B*, *G C*, *G D*, *G E*, *G F* with 1 or 2 per cent. loss wherever lights are to be furnished. Then by holding the voltage constant at *G* or slightly over compounding at that point, sufficiently good service can often be given.

If the loads are very unequal in size, *G* may be chosen at or near the most important point and lines run to the others as before, with the regulation question confined practically to the first. If the load points are quite numerous and scattered, Fig. 210 may be a preferable plan. Here two lines

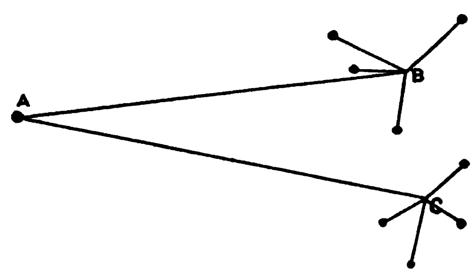


FIG. 210.

A B and *A C* are run and a group of load points is served from the terminal of each line. The groups shown are about equal, but sometimes it would be desirable to run a separate line for a single point where the load was peculiarly heavy or troublesome.

These scattered distributions are fortunately mostly for motor service, so that regulation, in practice, is often easier than the situation indicates. They sometimes run naturally into the linear distribution, which, unless of trivial size, is a thorn in the flesh of the engineer.

Fig. 211 is a type of this linear distribution, which is often met with in large transmission work and especially in long distance cases.

The power station *A* is mainly intended to supply lights and

power at *B*, which may generally be supposed to be the largest town in the immediate region. Incidentally it is highly desirable to supply lights and power to *C*, *D*, *E*, *F*, *G*, towns or manufacturing points at which electric power is needed. The main line *A B* may be taken as 20 miles, which is enough to disclose most of the difficulties.

Of course the line must be operated at high voltage with raising and reducing transformers. In nearly every case the

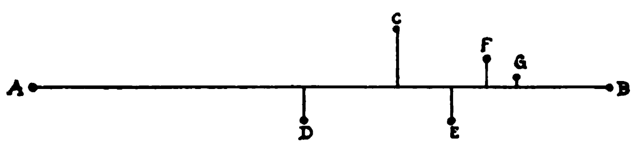


FIG. 211.

latter would be placed in a regular sub-station, with appropriate regulating apparatus for keeping uniform voltage throughout the primary and secondary networks in *B*. The loss of voltage in the line above may be assumed at 10 per cent. and the primary pressure at *B* as 10,000 volts. As *B* comprises by far the largest and most important part of the load, attention should be first directed to complete regulation at that point.

This can be best attained by first holding the primary pressure at *B* constant by compounding or other regulation at *A*, and second by careful regulation of the primary and secondary feeders in the sub-station. In fact the whole transmission must first be treated with respect to results at *B*, while nevertheless it is necessary to scatter power along the line at the points indicated. There may be present all sorts of requirements. For example, at *C* there may be required 1,000 incandescent lamps and a few motors; at *D* 500 incandescents; at *E*, a 50 HP motor and 300 incandescents, at *F* 300 incandescents, and at *G* 200 HP in motors and 200 lamps.

Frequently the load at one or more points may consist of motors only. This case is not included above, since no special regulation is needed; the power has only to be transformed from the line voltage to that of the motors, neglecting the effect of varying loss in the line.

Each of the cases noted involves the question of regulation in a somewhat troublesome form; at *D*, for example, the conditions under which incandescent lamps must be supplied are most severe. To begin with, at the nearest point of the main line *A B*, the voltage may change by about 6 per cent., owing to varying loss in the line; the branch to *D* causes a trifle more variation, the drop in the transformers still more, and finally there must be added the loss in the secondaries up to the lamps. In all, these cumulative variations in voltage may be 10 per cent. or more. At best, this means 5 per cent. change of voltage above and below the normal. This is too great to allow what can be called good service, although worse is sometimes given. In fact such variation ought to be classified as outrageously bad. To better matters, two methods are available.

First, one may use a hand regulator in connection with the reducing transformers; for, in so large a system as that involved, the changes in voltage are relatively slow, and the conditions of load may be such that over compounding on the main line may partially compensate for the losses elsewhere. Or second, the lights may be operated by a dynamo driven by a synchronous motor. This procedure adds somewhat to the expense and trouble but completely eliminates the loss in the line, since the speed of the motor is independent of the applied voltage, and incidentally, of the load.

For small outputs a good induction motor serves the purpose well, for it is simpler to operate than the synchronous variety and can be made remarkably insensitive to changes of load and voltage. This motor generator device is an admirable resource when a very variable line voltage must be dealt with. In making the installation for a point like *D* the actual variation of the pressure at the point of tapping the main line should be ascertained, and the effect of the subsequent losses up to the lamps should be computed. If the resultant changes are frequent and considerable, a motor generator gives the best result. For gradual and moderate changes an occasional touch at a regulator may be all that is needed, and now and then the resultant variation will prove to be not more than 2 per cent. above or below an

assumed normal for the lamps, in which case the regulation often may take care of itself.

At *C* there is a distribution equivalent to that from a small central station. The line pressure will generally have to be twice reduced before feeding the lamps. The choice of methods is the same as in the case just discussed, except that, with the losses of a double transformation and rather scattered service, regulation cannot be left to chance. In the majority of cases a motor generator sub-station would give the better results, unless the system is one in which from the nature of the distribution feeder regulators are desirable. In such case the regulation, since it must be accomplished, might as well be applied to the reducing transformers as to a special generator. A careful study of local conditions, however, is needful to enable one to discriminate between the two methods mentioned.

At the station *E* the motor will take care of itself, but the lamps might give trouble owing to variations in motor load. If these are great and sudden, nothing save running from the motor a generator for the lights will answer. If the load is steady and the lights regularly in use, as would be common in factory service, the loss in the branch line to *E* and the secondaries can be adjusted so that if the voltage at *B* is kept constant that at *E* will be nearly so. This device is probably the one best suited to give good service at *F*. For *G* the same method holds, but with so large a proportion of motor load, separate transformers for the lights are almost necessary.

The various cases of linear distribution just considered are of necessity treated little in detail, since they are so much modified in practice by special circumstances. Enough has been said, however, to indicate the methods to be followed and to show how tactfully this class of problems must be treated.

Finally comes that very important class of cases which involves the distribution of transmitted energy from large reducing stations. Such is the normal condition of affairs whenever power is transmitted to a city in large amounts for lighting and motor service. Passing over a few instances in which this power may be mainly utilized for driving by motors or replacing by rotary transformers existing central stations,

one is confronted by the problem of constituting a great distributing system for alternating currents; a system general enough to be available for every service, and perfect enough to compare favorably with the great networks now worked by continuous currents. Until very recently this problem would have been insoluble in any practicable way, but to-day, thanks to the modern alternating systems and to the intelligent use and arrangement of large transformer units, it is possible substantially to duplicate in convenience and efficiency the best direct current systems, while retaining the enormously valuable advantage of using high tension feeders. It must not be supposed, however, that the same procedure must suit both cases—the results and not necessarily the methods must be in full accord.

The basis of each system must be a carefully laid out network of working conductors, giving throughout the area of service a substantially uniform voltage as high as can conveniently be employed in the various consumption apparatus—lights, motors, and so forth. This voltage is practically determined by that of the incandescent lamps which are available. A few years ago 100 to 110 volts was the working limit of effective voltage between incandescent service wires (not of course the extreme voltage to be found between any two wires of the system). Of late the majority of important stations employ lamps of 115–120 volts. Now and then 120–130 volts is reached, and very recently there has been a strong movement toward boldly doubling the usual voltages and employing lamps made for 200–250 volts.

A considerable number of scattered small plants use such lamps, and in a few cases central stations have adopted them in connection with three-wire systems, using thus about 440 volts between the outside wires. There is a decided tendency in this direction, and occasional stations have undertaken to change to this double voltage, at least to the extent of trying 220 volt lamps extensively. At present these lamps are of somewhat uncertain quality and rather high price, but they have been rapidly improved, both here and abroad.

It is undoubtedly much harder to get an efficient and durable filament for 220 than for 110 volts at a given candle power. Such a filament is necessarily very slender and correspond-

ingly fragile. If two 110 volt filaments mounted in series would answer, the task would be simple, but such a combination gives double the required candle power, which is generally undesirable. The net result of present experience is that while 220 volt lamps can be made to give excellent results in efficiency and life (a recent test on a group of a dozen such lamps gave an initial efficiency of 3.1 to 3.2 watts per candle and an ultimate life of 3,000 hours or so), they are, as a rule, both poorer and costlier than the corresponding lamps of half the voltage. From the nature of lamp manufacture this condition is likely to remain, in perhaps lessened degree, even when the production of these high voltage lamps is extensive. The question between the two from a commercial standpoint will ultimately be a close one, although at present the advantage is altogether on the side of the lower voltage in most instances.

Until much experience has been accumulated with reference to the high voltage lamps, their use in any considerable undertaking cannot safely be recommended. It would be particularly unwise to attempt it in a large transmission plant, where any trouble with the lamps would inevitably be charged against the general system. It is better, then, to select for incandescent lighting a voltage only so high as has been thoroughly tried—say 115 to 120.

The resulting service voltage on the secondary network depends on the system of distribution employed. There are actually employed for primary or secondary distribution with alternating currents about a round dozen of distinct methods, more or less convenient and inconvenient, and requiring very various amounts of copper for distributing the same amount of energy at the same loss and distance. Several of them are very convenient and valuable, others have as their only excuse for existence the desire to exploit a novelty or to evade somebody's patent.

The simplest of them all is the ordinary two-wire system worked with alternating currents. In this the maximum voltage of the lamps is the maximum voltage of the secondary system. To avoid this limitation and to secure the ability to run motors is the principal function of the various modifications, polyphase and other, which make up the remainder. As these

various systems are often exploited it is worth the while to review them briefly, with special reference to economy of copper and convenience of installation on a large scale for the purpose we are considering. The two-wire system is shown diagrammatically in Fig. 212. Its main advantage is extreme

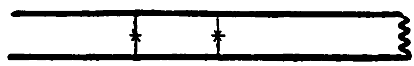


FIG. 212.

simplicity. It requires the same amount of copper as a two-wire direct current system at the same effective voltage, and is installed in the same general way, except that, owing to the peculiarities of alternating currents already explained, very large single wires are undesirable and armored conduits for underground service must be used with great caution.

As to motors for such a system the case is not altogether what one would desire. Alternating monophase motors are not yet so satisfactory for general service as those of some other types, more particularly as regards starting and severe service, and, until considerable improvement is made in them, the pure monophase system is severely handicapped. The two-wire arrangement is always at rather a disadvantage in the amount of copper required both for feeders and service mains.

The most obvious modification of this distribution is its evolution into a three-wire system such as is familiar in Edison stations. The extreme working voltage is at once doubled, and thus with the same voltage at the lamps, the cost of copper is greatly reduced. If the copper for a given two-wire system be taken as 100 that for the corresponding three-wire system is 31.25, assuming that the so-called neutral wire is of one-half the cross section of either of the others. Fig. 213 shows this familiar arrangement in diagram. Like every other system which saves copper, a three-wire distribution is subject to certain inconveniences. In the first place, it is necessary to carry three wires instead of two over substantially the whole working area. Secondly, the lamps must be nearly equally divided between the two sides of the system. This balancing of the load is not particularly troublesome in a well-

managed plant, and general experience has shown that the gain in copper far outweighs this disadvantage.

This three-wire distribution has been largely used for alternating current work. It is sometimes very convenient when applied to single or grouped transformers for the lighting of

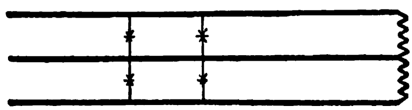


FIG. 213.

large buildings and regions in which balance of load is easily preserved. In such case the transformers are supplied from high voltage feeders, generally arranged on the two-wire system. As a rule, however, proper balancing is not easy in isolated districts and the best use of the three-wire system is for a general network of secondary mains, the potential of which can be controlled from a central station. In an ordinary direct current plant the feeders are of course at low voltage, and a great advantage is gained for the alternating arrangement by feeders at one or more thousand volts supplying the mains through transformers. As regards motors, the alternating current three-wire system is on substantially the same basis as the alternating two-wire system.

More complicated pure monophase systems are seldom used, although there is one instance at Portland, Ore., of a four-wire feeder system; derived, however, from polyphase generators. Fig. 214 shows the arrangement of the lines, which are

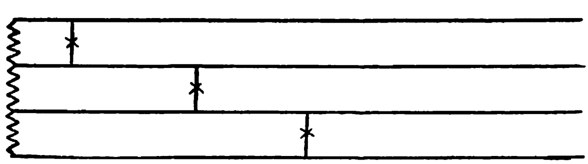


FIG. 214.

operated in general like a three wire-plant and require similar care in balancing, with the additional complication of running four wires and balancing three branches. The saving in copper is of course very great, the amount needed, allowing half the area of the outside wires for each neutral, being about

16.6 against 100 for the two-wire plant. The corresponding five-wire system may be passed over, as it is not used at all for alternating currents, nor extensively in any way.

Next in proper order comes the so-called monocyclic system, which is essentially a monophase system, but heterophase with reference to the operation of motors. Its principal features have already been explained. So far as lights are concerned, it is simply the monophase system already described in both the two-wire and three-wire forms. The "power wire," which supplies magnetizing current for the fields of the motors, is only used in so far as is necessary for its special purpose, and may or may not form part of the regular network. The two-wire monocyclic system shown in Fig. 215 describes itself.

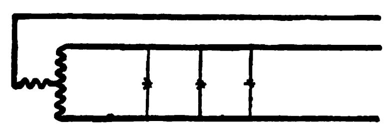


FIG. 215.

The expense and trouble of installing the "power wire" is the price paid for the ability to run motors. The total amount of copper is, of course, governed by the size and extent of the power wire. The main wires must accommodate the full current of the generator, for motors and lights must often be operated together, and at all events the machine must be fully utilized. The power wire, on the other hand, has to carry only a part of the current used in the motors. In a system heavily loaded with motors, the power wire might be one-half the cross section of each of the main wires. If then it extended over the entire system, it would add 25 per cent. to the copper required for the main circuit. Generally its size or extent would be less than that just noted. The total copper required for a monocyclic system is then variable. Its relative amount may vary from 100, when the system is operating lights alone, to 125 for rather extreme cases of motor load.

The same general properties hold good for the three-wire monocyclic system shown in Fig. 216. It is treated like any other three-wire system, except for the addition of the power wire wherever required. There is evidently a great saving of copper over the two-wire monocyclic, secured at the cost of running

an extra wire as a neutral and balancing the load on the two branches. The relative weight of copper varies from 31.25 for lights only to say 40 when the motor system is extensive.

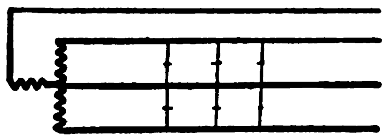


Fig. 216.

Either form of the system is singularly easy to install and operate in plants already having a considerable network of lines, since there need be no rearrangement or balancing of circuits, but only an additional line wire running to the motors installed and extended hand in hand with the motor service.

Passing now to the polyphase systems, it is well to reiterate what has already been stated in explaining them, viz., that they all involve about the same principles and lead dynamically to about the same results. They do, however, differ considerably in their characteristics as applied to a general system of distribution, and in rather interesting ways.

The diphase system can be worked either with four wires, *i. e.*, a complete and independent circuit for each phase, or with three wires. The former arrangement is the one almost invariably used. The two circuits can be worked independently for lights, but must be united to allow the operation of diphase motors. For the former purpose the two windings of the generator may be treated, save in one important respect, like separate monophase alternators. For the latter purpose they must work conjointly. Fig. 217 shows the relations of the

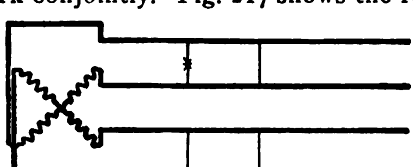


Fig. 217.

two circuits. In a general system it is the best plan to carry the two circuits throughout the territory to be covered. In this way motors can be run anywhere. Otherwise, if the main

circuits covered different districts, connecting lines might have to be run at considerable expense for copper and labor, uniting the two systems. Further, when the two circuits are together, it is easier to divide the load evenly between them; which is desirable to prevent one circuit of the generator being overloaded before the other is fully used. Incidentally hand regulation must sometimes be used for one or both circuits, unless the loads are equal as regards drop in the lines. If the generator is to be compound wound, the two phases must be equally loaded in order that the compounding may be able to hold the voltage on both phases alike. It must not be understood that unequal loads affect the voltage as in a three-wire system—they merely produce different "drops," in the two systems, which cannot be equalized by the generator.

As to the relative amount of copper required, it is, when both phases are run together, 100. If the phases are separated, this may be slightly increased by cross connections for motors.

A diphase system can be organized with each phase forming a three-wire system like Fig. 213. This doubles the working voltage and so saves copper, but at the cost of very serious complication. The full distribution requires six wires, three per phase, and these must be carried together or cross-connected for motors, if separated. The first procedure—running two three-wire systems side by side over the same district—involves frightfully complicated wiring; and the second, if the motors are at all numerous, requires a troublesome system of subsidiary lines. In either case, not only would each three-wire system have to be balanced in itself, but the two must be mutually balanced unless hand regulation is resorted to for one or both. Altogether the diphase system with separated phases does not lend itself readily to general distribution for lights and motors on a large scale. Its worst features are the large amount of copper required for secondary mains, and the forbidding complication of any attempt to secure economy by using the three-wire distribution. Like the diphase interconnected system about to be described, and certain forms of the three-phase system, it is most practicable in plants of moderate size not requiring a complete sub-station with a full system of secondary mains.

The interconnected diphase system, Fig. 218, employs a common return for the two phases. It has been often proposed but seldom used, for a good practical reason. The combined phases are unsymmetrical with respect to the inductance of the system, so that, even when the two sides of the system are equally loaded, the voltages between the common wire and the mains are unequal by an amount proportional to the inductive loss in the lines.

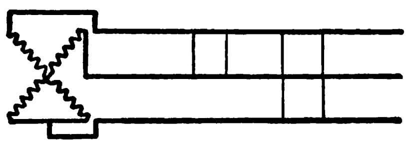


FIG. 218.

Hence it is unsuited for long lines either primary or secondary, overhead or underground. The lamps on the two sides of the circuit are at nearly the same voltage, but the voltage between the mains is so compounded of the two phases as to give increased working pressure enough to reduce the relative amount of copper to 72.8 under the most favorable circumstances. The system need scarcely be considered further, since it is more curious than valuable, and is unlikely to be employed in large substation work.

Three-phase circuits are variously arranged, as has been already indicated. The phases are very seldom separated, for a six-wire circuit is too complicated for general use, but are usually interconnected. The commonest and simplest connection is shown in Fig. 219. This consists of only three wires, each running from the terminal of a phase winding on the armature. Motors are connected to all three wires, and lamps between any two wires. The voltage is the same between each pair of wires, provided each pair be equally loaded. The relative amount of copper required is 75, as explained elsewhere. Here, as always, the uniting of circuits to save copper is accompanied by the need for balancing the loads. Not only does change of load on one branch change the drop in the other two, but interacts with them in the transformers and generator. The disturbance, however, is fortunately trivial in amount, except for very great inequali-

ties of load. With ordinary losses in the line it is absolutely negligible when the circuits at full load are balanced within 10 or 15 per cent., and at light loads far greater inequality will have no perceptible effect. With ordinary care in arranging the installation the question of balance never assumes any importance whatever, and need not do so even when very close regulation is desired. The main objection to the system of Fig. 219 is the considerable amount of copper required

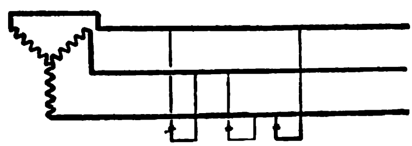


FIG. 219.

for a distribution by secondary mains as compared with the three-wire systems. Its salient advantage is its ability to handle motors and lights with equal facility on a system composed of only three wires and with some saving of copper. The trouble of approximately balancing the three branches is regarded as insignificant by those who are operating such systems.

A far better system for sub-station distribution is that shown in Fig. 220. It is a three-phase system with a neutral

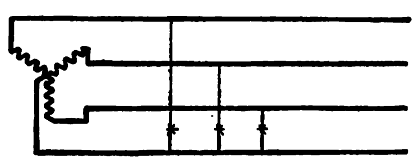


FIG. 220.

wire connected to the neutral point of the three-phase windings. The lamps are connected between this neutral wire and the several main lines. The result is that the working voltage of the lamps is the voltage from either line to the neutral point, while the working voltage of the system is 1.73 times greater; being the voltage between line and line. Hence there is a great reduction in the amount of copper required, the relative weight, as compared with the two-wire monophase system, being only 29.2 if the neutral wire is taken of cross section equal to one-half that of either of the other wires.

This system must be balanced approximately, but requires less care in this respect than the ordinary three-phase just described. It is on the whole better adapted for large distributions of mixed lighting and power than any other of the modern alternating systems, since it combines a fairly simple arrangement of wiring with very great economy of copper. It lends itself readily even to underground service, giving a rather simple cable construction and facilitating testing. It is used with excellent results in the Folsom-Sacramento and the Fresno transmission plants for the main work of distribution.

An interesting modification of the three-phase system is that used in the city of Dresden and shown in Fig. 221.

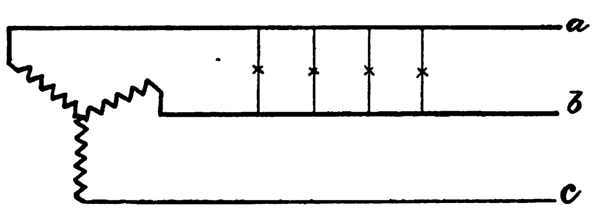


FIG. 221.

Here the system is constituted in the ordinary way, but two of the leads, *a* and *b*, are arranged to carry all the lighting, while the third wire *c*, which may be of much less area, is used only in connection with the motors. It may even be advantageous to increase the cross section of two of the armature windings at the expense of the third. A machine so constituted would have fully as great capacity as a monophase machine of the same dimensions, and still would be amply able to carry any ordinary motor loads. Obviously the relative copper required may vary from 100, when the load is of lights only, to 75 for the other extreme case. With half lights and half motors it would require 85–90 relative copper, according to the allowances made for drop, inductance, etc. In point of convenience it is very similar to the "monocyclic" system, and like the latter may be used with great ease in remodelling monophase systems for motor work.

A natural derivative of this mixed system is shown in Fig. 222. It is a combination of Figs. 220 and 221; *a* and *b* being

the mains, *c* the motor wire and *d* the neutral wire. The relative copper required naturally varies with the proportion of motors and lights; 36 representing that necessary for an approximately equal division under ordinary conditions. Fig. 220 may be compared with Fig. 216, the monocyclic three-wire system. It is about the same in effect as the three-phase system with neutral, having but two branches instead of three to balance, and paying for this privilege with about 20 per cent. more copper.

There is thus a liberal choice of methods more or less available for the general distribution of power and light. Any one

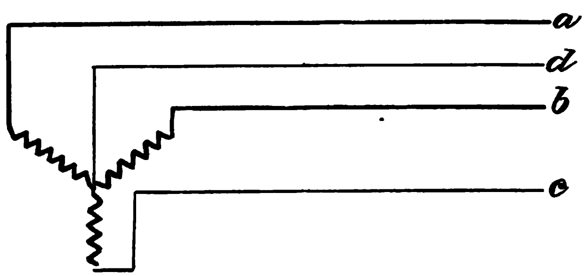


FIG. 222.

of them may prove to be the most useful in particular situations. Now and then it may be worth while to use more than one of them in the same plant, as, for example, monophase two-wire and monophase three-wire or three-phase and three-phase with neutral.

It must be borne distinctly in mind that one cannot organize a large sub-station distribution successfully on any substantially two-wire system—the cost of copper is too great. If work akin to that of a large central station is to be done, methods must be used akin to those which have proved successful in such work. The methods of distribution must be those which are capable of giving a secondary network of moderate cost, easy to install and maintain. The use of alternating current gives a great advantage in the use of high tension feeders and in efficient methods of regulation, and there is at present no difficulty in furnishing a reliable and efficient motor service; but to secure the full advantage of all this, one must cut loose from the traditions of alternating current service. A trans-

former must be looked upon not merely as a device for lowering the voltage to a point available for direct consumption, but as a generator of extreme simplicity and enormous efficiency that operates without attention, can be started and stopped from any convenient point, and may be regulated without material loss of energy. That it receives current from a transmission line instead of energy of rotation from a steam engine is clear gain in simplicity, not a marvel to be looked at askance. On the contrary, the transmission plant is usually quite as manageable and trustworthy as a steam plant.

Approaching the sub-station from this standpoint, the problem of effective distribution becomes tolerably straightforward. Given the transmitted energy, it must be distributed over a known area cheaply and efficiently, with the smallest feasible loss of energy at all loads, and the best regulation attainable. It will not do to plead transformer losses when the lights burn dim, or the depravity of alternating motors when they flicker.

First, as to locating a sub-station. On general principles any station should be placed as nearly as may be at the centre of its load, and inasmuch as a transformer station requires little space and makes little noise, there are few limitations to its position save the ability to bring to it the transmission lines, which, being generally at very high voltage, will be eyed cautiously by the municipal authorities. The main district to be covered is generally quite definite, and the next thing to be done is to reach every part of it with a network of working conductors proportioned to the service. The nature of the wiring will vary, according to the system employed; but the generally accepted principles are, save for inductance, the influence of which has already been considered, the same that are familiar in continuous current work.

The problem is to supply a certain amount of energy at a given loss over a known area, and the formulæ already stated give the key to the solution. Working out the details, however, is a somewhat complicated matter, requiring great judgment and *finesse*, and to be accomplished properly only by an experienced engineer, working on the spot. The intricacies of the problem are too great to be treated in an elementary treatise like the present. The general situation,

however, is something as follows: A city, Fig. 223, is to be supplied with light and power from a transmission plant. Let *A* be the centre of load at which the transmission lines terminate. At this point can most advantageously be located the reducing sub-station, lowering the voltage of transmission to perhaps 2,000 volts for feeders, or to a tenth of this for direct supply. The centre of load considered is not the geographical centre of the district to be supplied, but the centre of gravity of the

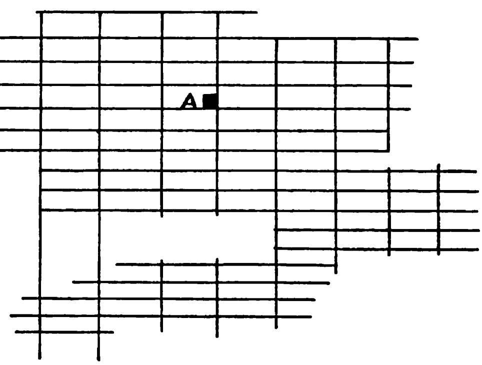


FIG. 223.

load. This is determined just as if the electrical loads at various points were weights fastened on a rigid framework. For example, suppose there are given the loads of Fig. 224, five in number and in relative magnitude as shown by the figures. Connect any two of them, as 1 and 2. These would balance as weights at the point *a*, which acts with respect to other points as if 1 and 2 were concentrated at it. Now connect *a* and 3. These weights are equal, hence the point of balance is the middle point of *a* 3, *b*, at which the weight is evidently 6; *b* 4 balances at *c*, where the weight is 10, and finally the whole system balances at *d*, which is the centre of gravity. The points may be taken in any order, but each line must be divided so that, for instance, the length *a* 1, multiplied by weight 1, shall equal the length *a* 2 multiplied by weight 2.

The centre of load thus found should be the centre of distribution to secure maximum economy in copper.

Recurring to Fig. 223, several methods of arranging the service are available. The simplest is, if the load is tolerably

concentrated, to institute a secondary network about *A* so as to include a good part of the load and then to pick up the outlying load by transformers, placed where they can do the most good, fed from high tension feeders. Sometimes, however, there will be no heavy service near the centre of load, so that the whole work of the station will be done through high tension feeders, each supplying through its transformers a more or less extensive system of secondaries.

As has already been pointed out, there is every reason for using a secondary network, connected directly to the reducing

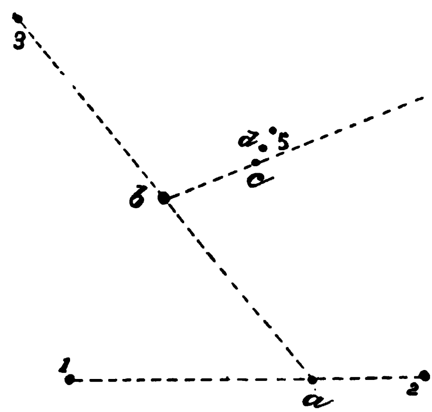


FIG. 224.

transformers, at the sub-station if possible, thereby avoiding the expense of transformers for a second reduction in voltage and the loss of efficiency involved in such a reduction. The house-to-house transformer distribution should be shunned as one would shun the plague, if there is any expectation of securing an efficient station, capable of giving first-class service.

It must be remembered that to be successful a modern plant for distributing power and light throughout a city must be able to compete with the best that can be done, not with the precarious and shiftless service of a dozen years ago.

It is possible with a modern alternating plant to equal the best service given by a continuous current central station, but the feat can be accomplished only by the study of central station practice.

The sub-station at *A*, Fig. 223, should be treated, so far as distribution is concerned, as if the reducing transformers were ordinary generators. The transformer units should be of the size that would be convenient if they were generators, and the bank should be so managed as to keep the transformers in use as thoroughly loaded as possible. From the transformer bank should run feeders to the principal sub-centres of distribution in the network, with boosting transformers and pressure regulators in such of the feeders as require them. From these sub-centres pressure wires should run back to the station for the guidance of the operator in charge of the regulators.

Outside the effective radius of distribution of the principal secondary network will come the independent sub-centres referred to, with their high tension feeders and subsidiary networks. These latter should be, so far as possible, interlinked so that, at times of light load, only the transformers actually needed shall be in service. If secondary pressure wires are brought home from the subsidiary networks all the regulation can be done on the high tension feeders, thereby giving equally good service all over the plant. Most continuous current stations extend their lines far beyond the radius that is economical for low tension currents, and often have to depend on boosters with feeders worked at a heavy loss for service in the outlying districts. With an alternating system this difficulty is avoided, and the loss in transformers and regulators is far less than that incurred with boosters and long low tension feeders.

As for the motor service in such a system, it should be treated by common sense.

Alternating motors, polyphase or other, can be connected to the secondary mains up to the point at which their demands for current become burdensome. At that point the mains must be reinforced or special feeders run, just as would be the case with continuous current motors. The only difference is that produced by the so-called idle current in the alternating motors, which simply means that the point in question is reached a little sooner than with continuous current motors. In practice this difference need not be enough to be of serious moment in plants having the ordinary proportions of lights and motors. In case of large motor plants in which the service

is severe, the use of special high tension feeders will relieve the trouble that might be experienced with the lights, but this expedient is one to which recourse would seldom have to be taken on a large scale.

The greatest difficulty in such sub-station distribution is, as has been already indicated, the arc lighting. At present the alternating arc lamp is hardly adequate to meet all conditions. It is coming gradually into more and more extended use, but there seems little prospect of its replacing the regular arc systems for all-around service. Under these conditions it is probable that the best plan is to run regular arc circuits wherever necessary. These may be supplied with current in various ways. The most generally useful, particularly in cases where a transmission plant replaces existing electric systems, is the very obvious device of driving arc generators from synchronous motors. This involves some loss of efficiency but gives excellent service, and it is quite probable that the light per kilowatt obtained in this way is as great or greater than with alternating arcs.

Rectifying apparatus, such as the Ferranti machines already described, gives a considerably higher efficiency and is a promising method for future development. At the present time it is not used extensively enough to warrant unqualified confidence.

In cases where power is to be supplied for railway purposes, there are few difficulties in the way. Existing railway generators can readily be utilized by driving them from synchronous motors. This is the method employed in the long transmission to Sacramento, Cal., and elsewhere not infrequently. Where the utilization of the old machine is not important, or in new plants, the tendency is to use the rotary converter, which has been already fully discussed. Such apparatus was first put into extensive use in the Portland (Ore.) transmission plant, and is now largely and very successfully employed elsewhere. Continuous current for other purposes may be obtained with ease by the various methods described in Chapter VI.

The most delicate and important work in connection with heavy sub-station service is that involved in the proper regulation of the voltage. The sub-station receives its supply of

energy often from a long transmission line in which there is considerable drop, to say nothing of that encountered in the generators and two banks of transformers.

It must distribute this energy throughout a complicated network, so that the variations in pressure at the lamps shall not exceed two or three volts at the outside. This is never an easy task—it tries the ingenuity even of the best central station engineers.

In connection with a transmission plant probably the best

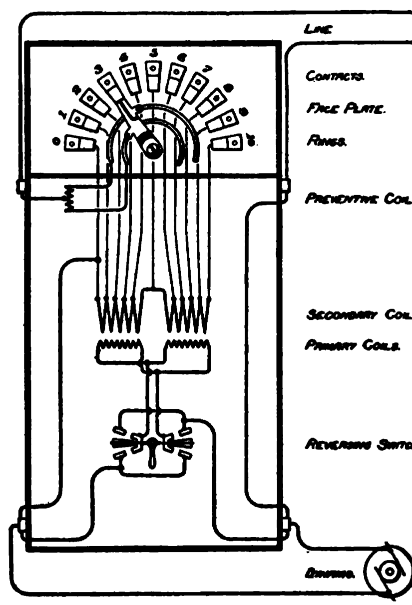


FIG. 225.

plan is to divide the regulation into two stages: first that concerned with the transmission proper, and second that concerned with the distribution. By compounding the generators, or by hand or automatic regulation of generators having good inherent regulation, it is certainly possible to hold the voltage closely constant up to the primary terminals of the reducing transformers. This leaves to be accounted for, the drop in the reducing transformers, which should be not over 1.5 per cent.; the drop in the feeders and secondary mains; in high tension

feeders and transformers when employed; and finally in the house wiring. These losses will aggregate generally less than 10 per cent., and must be cared for in the sub-station. As the variations in load and hence in loss are generally rather slow, this regulation should be accomplished without difficulty. In some cases it may be advantageously reduced in amount by carrying the primary regulation through to the secondary terminals of the reducing transformers.

However this may be, the regulation of the voltage on the secondary lines must be carried out with the utmost care. The apparatus employed for this purpose is both very simple and exceedingly efficient. It is in every case a transformer arranged to give a variable ratio of transformation and adding its E. M. F. to that of the working circuit.

The best known form of this device is probably the Stillwell regulator, which has for some years past been very successfully

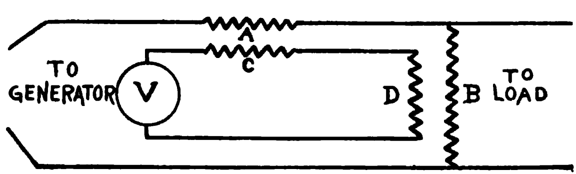


FIG. 226.

used by the Westinghouse company. It is, in effect, a transformer, from the secondary coil of which leads are brought out to terminals so arranged as to enable one to vary the number of secondary turns, and so to vary the E. M. F. added to the working circuit. Fig. 225 shows a diagram of the connections by which this result is effected. The diagram is self-explanatory, except that it should be noted that the "preventive coil" is intended to avert the necessity of breaking circuit or short circuiting a secondary coil in passing from one contact to the next, and that the reversing switch enables the regulator to diminish the voltage on the working circuit, which may now and then be convenient. In the ordinary practice of the Westinghouse company this regulator is installed in the generating station and used to vary the voltage on the primary line. In sub-station work it can be applied either to the primary or

secondary side of the reducing transformers; practically the latter is the working connection. These regulators are made to have a range of action of 10, 15 and 20 per cent. of the working voltage. They are generally employed with a very ingenious device known as the "compensator," the function of which is to indicate the pressure at the end of the line or feeder without the use of pressure wires. The principle of this is shown in Fig. 226. The voltmeter *V* is in circuit with the opposed E. M. Fs. of two secondaries *C* and *D*, of which the primaries *A* and *D* are respectively in series and in shunt with the load. The voltage of *D* is proportional to the main primary E. M. F., that of *C* to the primary current strength, so that the difference between *C* and *D*, which shows on the voltmeter, can be made proportional to the voltage as reduced by the drop due to the current in the line. The compensator is in addition provided with a series of contacts by which the E. M. F. of *C* is adjustable for any given percentage of loss in the line.

The practice of the General Electric Company is somewhat different. The generator is generally over compounded for a fixed loss in the line at full load, or pressure wires are used and regulation effected by the field rheostat. For sub-station purposes a variable transformer is employed to vary the working voltage. The principle of this voltage regulator is the variation of the inductive relation of primary and secondary instead of varying the number of secondary turns. The apparatus itself is made in several forms, one of which, used in the Portland (Ore.) three-phase plant, is shown in Fig. 227. It is essentially a transformer with a movable secondary, and serves either to raise or lower the working voltage, as occasion requires. The gradation of voltage is not by definite steps but by continuous variation. The apparatus is made for substantially the same range of action as the Stillwell regulator just described, and accomplishes the same result.

It should be stated that neither the "compensator" nor over compounding can deal successfully with a load of variable inductance, such as is often found in motor service. Both devices can be made to work well on either non-inductive *or* inductive load, but neither is adapted for a load of which the power factor varies much. For this condition nothing has yet

been devised so good as pressure wires combined with intelligent hand regulation.

Various attempts have been made to employ pressure wires in conjunction with automatic regulators, but none have yet met with very encouraging success.

The devices just described are amply competent to furnish very exact regulation for sub-station purposes. Its completeness depends in the last resort on the skill with which the distributing system is designed. If this is carefully done, the

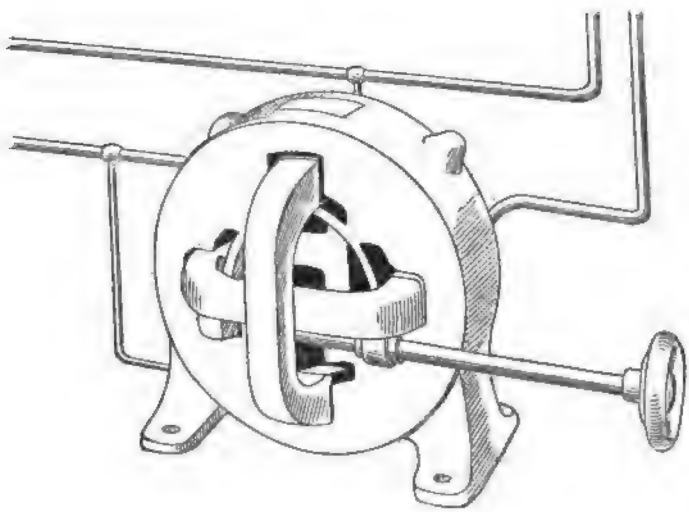


FIG. 227.

sub-station regulation should hold the voltage within very narrow limits clear up to the lamps.

As regards the best system of transmission to employ in connection with heavy sub-station work, there is naturally a wide diversity of opinion. In the author's judgment there is at present no distributing system for large sub-station work so generally advantageous as the three-phase distribution with neutral wire shown in Fig. 220. It is remarkably free from trouble as regards balancing, and extraordinarily economical of copper. With further advance in the development of single-phase alternating motors, the single-phase three-wire system shown in Fig. 213 will do admirable work when the motor

service is only moderately large. The diphase system is being installed in one large central station and the "monocyclic" in another, so data will soon be available regarding each of these systems, but there is little reason to expect as good general results as could be obtained by the systems mentioned above. Both diphase and monocyclic systems are, however, very much easier to adapt to the circuits of present stations than is the three-phase system with neutral wire.

When a large part of the output of a transmission plant is required for railway work and other motor service of extreme severity, and a lighting system is also to be operated, it is a wise precaution to work the two services normally over separate lines and from separate generators. Otherwise the variations of load may be so great and so rapid that no care in regulation could prevent serious fluctuations in voltage. A small railway load and all ordinary motor service can be worked from the same circuits as lamps without any difficulty. These limitations are not peculiar to transmission plants—no Edison station, for instance, would dare to attempt working a low voltage conduit railway from its lighting mains. In these, as in many similar matters, a little common sense will prevent serious mistakes and show the necessity of working every system so as to obtain the best possible results, and not to discover what it will endure without giving intolerably bad service.

CHAPTER XIII.

THE COMMERCIAL PROBLEM.

Power transmission is of little avail if it does not pay, and the chances of commercial success form the first subject of investigation in the development of any power transmission enterprise. Reduced to its lowest terms, the question presents itself thus: Can I profitably furnish power at a price which will enable me to undersell the current cost of power production? Evidently this question cannot be answered *a priori*, but must be thoroughly investigated in each particular case.

The first thing to be determined is the existence of a sufficient market, the second thing is the price current in this market. It is not difficult to find out the gross amount of power used in a given region, but it is exceedingly hard to discover the real cost of production. Even if all men were strictly veracious it is a fact that very few users of power have any clear idea of what they pay for it. Coal bills and wages are tangible and men realize them, but interest, depreciation, repairs, miscellaneous supplies, water, taxes, insurance and incidentals, are seldom rigorously charged up to the power account, and these are large items when power is used irregularly.

Further, the cost per HP is often computed from the nominal HP of the engine, without exact knowledge of the real average yearly load. Hence people often think that they are producing power at $15 or $20 per HP per year when the real cost is $30 to $50.

The most exhaustive researches as yet made on this subject are those of Dr. C. E. Emery. The accompanying table gives a summary of his results, based on 500 net HP delivered for 10 hours per day, 308 days in the year. The power is supposed to be derived from a single engine worked continuously at its normal capacity. These figures represent results

much better than are generally reached in practice, since most engines are not worked continuously at full load. In a large

Kind of Engine.	Coal $2 per T.	Coal $3 per T.	Coal $4 per T.	Coal $5 per T.
Simple high speed	$29.81	$36.17	$42.54	$48.90
Simple low speed	28.46	34.20	39.94	45.67
Simple low speed, condensing	22.82	26.77	30.73	34.69
Compound condensing, low speed	21.97	25.53	29.09	32.65
Triple expansion condension, low speed	22.35	25.32	28.28	31.25

majority of cases the real cost exceeds that given in the table by something like 50 per cent., even for engines of similar size. For the rank and file of small engines used for miscellaneous manufacturing purposes, cheaply built and generally under loaded, the tabular figures should be just about doubled. In regions where coal is unusually dear the cost in units of 50 HP and upward may range from $100 to $150 per HP year for a 10 hour day.

In units under 50 HP one is very unlikely to find the HP year, reckoned on the above basis of 10 hours per day, costing less than $50, even with coal as low as $2 per long ton. These are the facts in the case; the fancies will be duly appreciated if one canvasses for electric power. Not more than one man in six knows and will admit that his power is costing him as much as the table would indicate. The process of reasoning (so called) is often about as follows: "I paid for my engine and boiler house when I built the factory, and I do not propose to charge my engine rent. It has been running ten years and is just as good now as it ever was; has not depreciated for my purpose a cent. If any repairs are needed, the engineer and one of my men have made them and they haven't cost me anything but my material. My fireman I have to have anyhow, for I heat by steam, and my taxes and insurance I have to pay anyhow: that is a 200 HP engine; my coal cost me $2,450 last year and oil and stuff $70. I pay my engineer $60 a month; that's $16.20 per horse-power per year; if you can furnish electric power for $15 per year perhaps we can trade." This

theme, with variations, is familiar to anyone who has had practical experience in power transmission work, and although the more intelligent and able class of manufacturers are quite too keen not to see the facts when properly presented, a certain amount of this ignorant short-sightedness is always met in investigating the power market.

With a working year as above of 3,080 hours the cost of steam power is actually very seldom as low as 1 cent per HP hour, and in units below 100 HP is not very often below 2 cents. In units of less than 20 HP it is quite certain to be 5 cents or more. These figures are based on continuous working. If the use of power is intermittent, the cost per HP hour is greatly increased, by an uncertain but always large amount, depending on the nature of the service. For highly intermittent service gas engines are undoubtedly cheaper than steam, and in ordinary units the cost of operating these is seldom less than 10 cents per HP hour of use. Used continuously at full load or thereabouts the gas or petroleum engine is the most formidable competitor of electric motors, since the actual cost of fuel is low—from 2 to 5 cents per HP hour—and the attendance required is trifling. Such engines, however, are high in first cost and are very inefficient at low loads, besides being subject to relatively large depreciation.

These peculiarities are well shown in a recent test of a 6 HP gas engine in which the following facts appeared: The cost of operation, including maintenance, was at full load 41 cents per hour, and at no load 20 cents per hour; the cost of gas being $1.70 per M feet.

We may easily find from this the cost of power under given circumstances of use; $10 per HP per year may fairly be charged up to interest and depreciation. Suppose now, power is used for 10 hours per day 308 days in the year, the engine being fully loaded all the time. The cost can be made up as follows for 6 HP:

3,080 hours @ 41 cents, ...	=	$1,262.80
Interest and depreciation, . .	=	60.00
Total cost, ...	=	$1,322.80

Cost per HP hour = 7.15 cents, of which the interest and depreciation amounts to but 0.31 cents per HP hour.

Second, suppose the engine is in full use 3 hours per day, and running idle the rest of the time, or is in equivalent partial use for 10 hours. We then have

924 hours @ 41 cents, ...	= $378.81
2,156 " " 20	= 431.20
Interest and depreciation, ...	= 60.00
	$870.01

This is 12.08 cents per HP hour actually used, and is a fair type of present practice as gas engines are generally used. It will hold for the average engine used for small power purposes. In regular running such engines consume from 25 to 35 cubic feet of average illuminating gas per brake HP and, when running light, take about half as much gas as at full load. In careful experimental running these results can be bettered 10 to 20 per cent., but in regular work and with only ordinary care, the gas consumption given is correct.

Petroleum engines give rather less fuel expense, but lose in extra care and repairs nearly or quite all the gain in fuel.

These figures must not be understood as applying to large gas engines of 100 HP and upward, worked on cheap "producer" or fuel gas. It is reasonably certain that such engines give results better than any save the most economical steam engines, if worked at or near full load. In the small sizes above considered the gas engine is a considerably cheaper source of power than steam engines, probably by not less than 30 per cent.

In a general way we may summarize these facts regarding cost of power as follows, coal being taken at $3 per ton:

KIND OF ENGINE.	COST PER HPH, 10-HOUR DAY, FULLY LOADED.	COST PER HPH, INTERMITTENT USE, PARTIAL LOAD.
Large compound cond.	0.8c. to 1c.	1c. to 1.5c.
Simple, 100 HP and less	1.5 " 2.5	3. " 5.
Gas, 20–50 HP	2.0 " 4.0	4. " 7.
Gas, small	5. " 8.0	10. " 15.
Steam, small	7. " 12.	12. " 20.

By small engines are meant those not over 15 to 20 HP, such as are used in large numbers for light manufacturing work. These figures are of course only approximate, and must be modified by the cost of fuel and labor in any particular locality.

They take no account of the efficiency lost between the engine and its work, which has been already discussed in Chapter II., and which gives motor service some of its greatest commercial advantages.

They show plainly, however, that electrical energy delivered to the consumer at 4 to 5 cents per kilowatt hour has the commercial advantage in small work of all kinds, and in competition even with fairly large engines used at light load or intermittently. In addition there is, in favor of electricity, the generally considerable saving in waste power, and the greater cleanliness and convenience of the motor. At equal prices electric power will pretty effectively keep steam out of all new work, but the cost of changing from one motive power to the other demands some concessions on the part of electricity.

This cost of change is rather uncertain, for not only do electric motors vary very widely in price, owing to differences in size, speed, and construction, but the net value of engines and boilers replaced may vary from two-thirds to three-quarters of their cost down to little more than scrap.

In both engines and motors the cost of the smaller sizes is disproportionately large, owing to the relatively large percentage of labor in their construction. Gas engines are even more expensive than a steam boiler and engine in ordinary sizes. In replacing engines by motors, the selling value of the former, including boilers, if steam is used, may be anything, say from $10 to $25 per HP, and the market is rather uncertain at best. A little time will generally effect a sale on tolerable terms.

The following table gives the approximate cost of electric motors installed and ready to run, based on motors of ordinary speeds and voltages, with the usual accessories and with the simplest sort of wiring. No useful figures can be given on the cost of special installations with complex wiring.

From this it appears that while large motors, 50 HP and upward, can generally be counted on at not over $25 per HP, the smaller sizes are much more costly. Below twenty HP the net cost of changing from steam or gas engines to motors is pretty certain to be $20 to $30 per HP. Taking interest and depreciation at 10 per cent., the annual charge amounts to $2 or $3 per HP, which must be increased to $5 or $6 to cover maintenance and miscellaneous expenses.

Hence, for steady use 10 hours per day, there should be charged to general cost about 0.2 cent per HP hour, which is equivalent to perhaps 0.5 cent for intermittent use.

HP.	Cost.
1	$ 100 to $ 125
3	175 " 250
5	225 " 275
10	325 " 425
15	350 " 450
20	450 " 600
25	550 " 700
30	650 " 800
40	800 " 1,000
50	900 " 1,150
75	1,400 " 1,700
100	1,900 " 2,300

In changing motive power, then, electric service must generally be cheaper than what it replaces by about the amounts mentioned.

As to the cost of furnishing electric power figures are a little deceptive, since from place to place the conditions vary. It is safe to allow about one KW at the station for one HP actually delivered.

Now with steam for a motive power the data already given for mechanical power can readily be reduced to kilowatt hours, assuming the dynamos to have as usual 92 to 95 per cent. efficiency at full load. But a steam station for power transmission has the advantage of nearly or quite continuous running, thereby reducing general expenses, and besides, on a large scale, the load can be kept at an efficient point most of the time. In fact in large railway power stations—the only steam-driven stations for power transmission on a large scale—the machines can be worked very efficiently most of the time, and power can be, and is, very cheaply produced.

Fig. 228 shows graphically the approximate variation of cost with output in well-designed power stations, the figures given being based on $3 per ton for coal and power delivered at the station bus bars. Anything under one cent per KW hour is good practice, even for a very large station. Steam is not likely to be often used as a motive power for power transmission work, except in working a very cheap coal supply.

Dr. Emery has worked out at considerable length the problem of the cost of steam power on a very large scale and with the most economical modern machinery. He assumed a 20,000 HP plant, worked 24 hours per day, on a variable load averaging 12,760 HP, 63.8 per cent. of the maximum. This

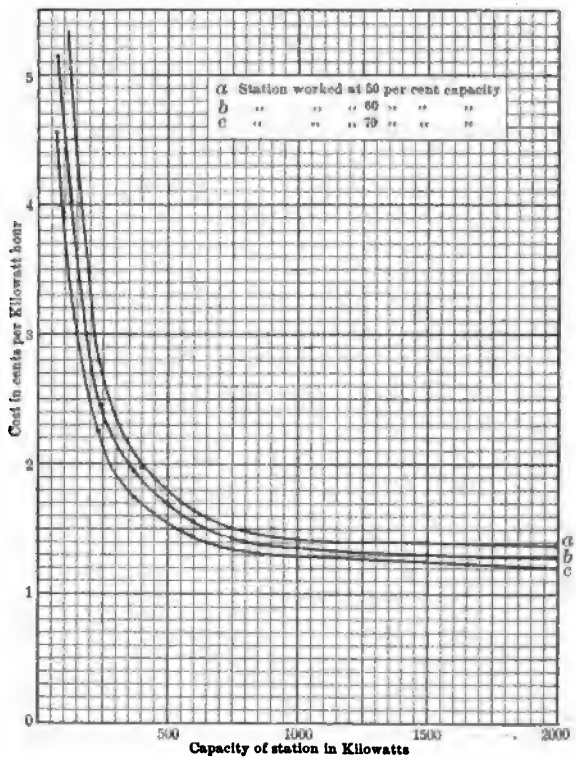


FIG. 228.

load factor is judiciously estimated and could certainly be realized in a plant of such size, employed in the general distribution of power. Taking coal at one mill per pound, $2.24 per long ton, and entering every item of expense, he found the total cost per HP per year to be $33.14. If the plant were established at the mouth of the coal mine, fuel should be obtained at not over one-third the above cost. This advantage would bring the cost per HP per year down to $24.89.

Taking now 15,000 KW in dynamo capacity in large direct coupled units, say eight in number, the electrical plant would cost, installed with all needful accessories and ready to run, $375,000. Taking interest, taxes and depreciation together at 10 per cent., which is enough, since a 3 per cent. sinking fund would amply allow for depreciation, allowing $15,000 per year for additional labor and superintendence and $10,000 more for maintenance and miscellaneous expenses, brings the total annual charge for the electrical machinery to $62,500. Adding this to the steam power item and reducing the whole to cost per KW hour, assuming 94 per cent. average dynamo efficiency, the total cost per KW hour delivered at the station switchboard becomes 0.482 cent. Working, then, on an immense scale from cheap coal, it is safe to say that half a cent per KW hour will deliver the energy to the bus bars.

The next step is the cost of delivering it to the customer. This varies so greatly, according to circumstances, that an average is very hard to strike. A plant such as we are considering will usually be installed only when the radius of distribution is fairly long. Taking the transmission proper as 20 miles, the line and right of way, using 10,000 volts, may be taken as about $25 per KW; the raising and reducing transformers with sub-station and equipment would cost another $25 per KW, and the distributing circuits, with a good proportion of large units, about $5 per KW additional. The distributing system for 15,000 KW would then cost about $975,000. Figuring interest and depreciation roundly at 10 per cent. the annual charge is $97,500. Add now $15,000 for labor in sub-station and distributing system, $10,000 for general administrative expense, and 5 per cent. for maintenance and miscellaneous expenses, and we reach a total annual charge for distribution of $171,250. The average output being almost exactly 9,000 KW, the cost of distribution per KW hour is 0.218 cent. The actual cost of generating and distributing the power then becomes 0.700 cent per KW hour.

This is probably a minimum for distribution of power from coal mines. It supposes a very large plant installed for cash and operated for profit. It makes no allowance for the floating of bonds at 60 to 80 cents on the dollar, the operations of a construction company, the purchase of coal from the direct-

ors, the payment of big salaries to the promotors, or any of the allied devices well-known in financial circles.

Under favorable circumstances at least an equivalent result can be reached with hydraulic power.

These figures mean that power could be sold at an average of 1 cent per KW hour at a good profit, aggregating for the plant in question nearly a quarter of a million dollars per year.

Only the largest plants, skillfully handled, can approach such figures for cost of power as have just been given.

It should be possible, however, to bring the cost of distribution per KW hour in a well-designed transmission plant of 1000 HP or more down to less than 0.5 cent per KW hour. Less than this may indeed be found in practice, while figures approaching 0.25 cent may be found in good central station working.

The cost of producing power in steam-driven plants of various sizes has already been given; that in water power plants is far less definite, but on the whole lower. In some hydraulic plants where development has been costly, the cost of water power rises to $20 or $25 per net HP year, while on the other hand water power has been leased at the canal for as little as $5 per year per hydraulic HP in the canal, equivalent to about $6.50 per available HP at the wheel shaft. The investment per effective HP at the wheels ranges from nearly $150 to as low as $30 or $40. This includes both the hydraulic rights and work, and the wheels themselves.

A typical estimate for a water power plant under fairly favorable conditions, derived from actual practice, runs about as follows, for a 1000 HP plant:

Hydraulic works,	$40,000
Wheels and fittings,	12,500
Power station,	2,500
Pole line, 8 miles,	4,000
Transmission circuit,	15,000
Dynamos and equipment, 700 KW,	20,000
Transformers, 750 KW,	10,000
Distributing lines,	15,000
Miscellaneous,	5,000
Total,	$124,000

Operating expense:

Interest and depreciation, 10 per cent.,	$12,400
Attendance at plant,	4,000
Linemen and team,	2,000
Office expense,	3,500
Rent, taxes, and incidentals,	1,000
Maintenance and supplies,	4,000
Total,	$26,900

The full capacity of the plant is about 700 KW. Supposing the plant to be worked somewhere near its capacity at maximum load, and to be in operation on a mixed load 24 hours per day, we may estimate the daily output about as follows:

KW	KWH
9 hours @ 500	4,500
5 " " 250	1,250
3 " " 100	300
6 " " 50	300
Total,	6,350

This should be taken for 300 days in the year. The other 65 days, Sundays, holidays and occasional periods of unusually small motor loads, it is not safe to count on more than 1,000 KW hours per day. Taking account of stock we have for the year

1,970,000 KWH,

and the net cost per kilowatt hour becomes 1.36 cent. It is worth noting that the distribution of power for the day is taken from a transmission plant in actual operation.

Of the above total cost 0.47 cent is chargeable to distribution expenses and 0.89 to power production. Doubling the cost of the hydraulic works would raise the generating cost to 1.10 cent and the total cost to 1.57.

It is evident in this case that power could be sold at 2 cents net per HPH with a good profit, assuming the smaller total cost, and at 2.5 cents, even with the greater hydraulic cost. Even if the total investment were as great as $250,000, the plant would pay fairly well at 3 cents per HPH.

The fact is, hydraulic transmission plants generally will pay well if a good load can be obtained. The above example does not show a specially cheap plant nor a remarkable load factor.

In really favorable cases the cost of power distributed will not exceed 1 cent per HP hour, and in comparatively few plants will it rise to 2 cents, unless the market for power is grossly overestimated.

This is one of the commonest troubles with plants that do not pay well. A costly hydraulic development is undertaken, resulting in rendering available several times as much power as can be utilized; a portion of this is then transmitted and sold, but the plant is burdened with heavy initial expense, and struggles along as best it can. It is not safe to count on the stimulation of industrial growth by cheap power unless the cost of producing power is so small that the plant will pay tolerably well on the existing market.

A careful canvass for power is a necessary part of the preliminary work for a power transmission, and the more complete it can be made the better. Reference to the table of p. 474 shows that, at a selling rate of 2 to 3 cents per HP hour, the cost of power can be reduced for all small consumers and a good many rather large ones. If the cost of coal is high, $5 per ton or more, nearly all consumers will save by using electric power, while with favorable hydraulic conditions money can be saved by transmission even when replacing very cheap steam power.

Take, for example, a large manufacturing plant requiring 1,000 HP steadily, 12 hours a day. At a distance of, say 8 miles, is a hydraulic power that can give, say 1,200 HP, and can be purchased and developed for $100,000. The cost of generating and transmitting power will be about as follows:

Hydraulic work,	$100,000
Wheels and fittings,	15,000
Power house,	3,000
Pole line,	4,000
Dynamos, 1,000 KW,	25,000
Transmission circuit,	15,000
Motors and equipment,	25,000
Miscellaneous,	10,000
Total,	$197,000

and the operating expenses would be about as follows:

Interest and depreciation,	$19,700
Attendance at plant,	2,500
" " motors,	1,800
Other labor,	1,000
Maintenance, supplies, etc.,	5,000
Total,	$30,000

This would furnish, taking the working year as 308 days, 3,696,000 HP hours at a cost of 0.81 cent per HP hour. With a low cost of hydraulic development and a short line, say not over three miles, the above figures for cost could be brought down to about $130,000. Now, allowing 5 per cent. for interest and setting aside 3 per cent. for sinking fund, which allows for complete replacement in less than 20 years, we may figure the annual cost of power again thus:

Interest and sinking fund,	$10,400
Attendance at plant,	2,500
" " motors,	1,800
Maintenance and incidentals,	5,000
Total,	$19,700

This is $19.70 per HP year, or 0.53 cent per HP hour. This is eertainly cheaper than power can be generated by steam, even with coal at $1.50 or so per ton, provided proper account be taken of interest, depreciation and repairs. As a matter of fact, the cost just given has been reached, in practice, in transmission work at moderate distances. On a larger scale slightly better results can be attained. These figures take no account of the saving in actual power obtained by distributed motors, always an important matter in organizing a transmission for manufacturing purposes. This can generally be counted on to make it possible to replace 1,000 HP in a steam engine by not over 750 HP in electric motors, with a corresponding reduction in the aggregate yearly cost of power.

Speaking of costs in a general way, dynamos and their equipment may safely be taken at $25 per kilowatt, raising and reducing transformers at from $8 to $12 per KW, line erected at from $10 to $30 per KW, water wheels at $10 to

$20 per HP, and steam plant, when used, at from $50 to $60 per net HP.

The line is always a rather uncertain item, on account of its variations in cost at different distances, and in meeting local conditions of distribution. The pole line itself will cost from $250 to $500 per mile, according to circumstances, but the copper must be figured separately, as explained in Chapter X.

No account is here taken of freaks in design—dynamos of special design for peculiar speeds or voltages, extraordinary line voltages, unusual frequencies, or eccentric methods of distribution like the wholesale use of rotary converters and storage batteries. The figures are intended to represent ordinary good practice as it exists to-day.

One of the nicest points in operating a transmission plant is the proper adjustment of the price of power to the existing market. It is no easy matter to strike the point between the cost of other power and the cost of generating and distributing electric power, which will give the maximum net profit. In general it is best to work entirely on a meter basis, for the customer then pays simply for what he uses, and the station manager knows the exact distribution of his output.

The generating station or the sub-station should be equipped with a recording wattmeter that will show the actual output, and from this measurement much valuable information can be obtained.

Knowing the investment and the approximate operating expense it is easy to figure, as we have just done, the total cost of delivering energy per KW power at various outputs. This is the basis of operations. The next thing is to estimate as closely as possible the average local cost of power in units of various sizes. These two quantities form the possible limits on selling price. One must keep far enough above the first to insure a good profit, and enough below the second to capture the business. It is convenient to plot these data as in Fig. 229, which is based on the table of p. 474, and the plant discussed on p. 480. Curve 1 shows the effect of change in the annual output on the net cost per KWH. Curve 2 shows the approximate existing cost of steam or other power, the points from which the curve was drawn being shown by crosses. Curve 3 shows the same for intermittent loads, the

points being indicated by circles. It is evident that for yearly outputs less than 1,000,000 KW hours the plant would be in bad shape to get business. At 2,000,000 KWH good profits are in sight, while at 3,000,000 it can meet all cases at a profit.

At the given output of 1,970,000 KWH it would be possible to charge 2 cents per KWH as a minimum without

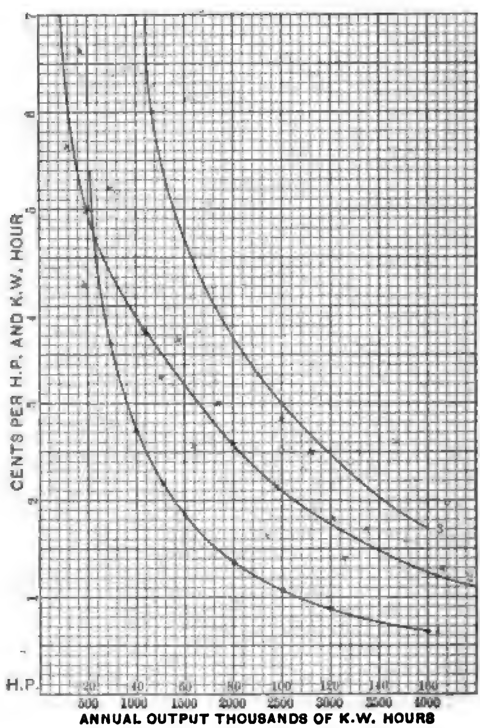


FIG. 229.

losing much business, while all the smaller customers could gain by changing to electric power at 3, 4 or 5 cents per KW hour.

When a few consumers are generating power at an unusually low figure there is always the temptation to obtain them at a special cut rate. As a rule this is bad policy unless they

are desirable for some particular reason aside from increase of output, for the moral effect of special low-price contracts is always bad, and in the long run it is best to make standard rates and adhere to them.

The best prices can always of course be obtained from small consumers, and these are also specially desirable in that they tend to keep a uniform load on the system. Not only do 50 10 HP motors yield several times as much revenue as one 500 HP motor, but they will call for power very steadily all day long and keep the regulation excellent, while the large motor may be off and on in the most exasperating way and cause great annoyance at the time of the "lap load," when lights and motors are all in use. Large motors running intermittently are disadvantageous, for they do not greatly increase the aggregate station output and pay relatively little.

In general the best schedule of prices can be made up by starting with a rate arranged to get all the powers below, say 4 or 5 HP, and then for larger powers arranging a set of discounts from this initial rate. These discounts, however, should be based not directly upon the size of the motors, but on the monthly KW hours recorded against them.

A water power transmission plant has the peculiarity, when, as usual, the water is owned outright, of showing a nearly constant operating expense, irrespective of output. Hence after the receipts exceed this expense all additional load, at any price, means profit. But it means profit precisely in proportion to its price, so that taking on large consumers at a very low price is usually bad policy, it being better to encourage small consumers by giving what is to them a very reasonable figure.

In the case in hand, it would probably be worth while to start as low as 5 cents per KW hour on a monthly consumption up to 1,000 KW hours. This corresponds nearly to 4 HP used continuously 9 hours per day. For 100 HP so used it should be possible to get 2 cents per KW hour, so for a consumption of 25,000 KW hours per month the discount fixes itself at 60 per cent. For intermediate points the proper discounts are fixed in a similar manner. A uniform discount of say 10 per cent. from bills for payment before a fixed date is generally good policy. The rates of discount should be set

bearing in mind the distribution of business with respect to the size of units, the intent being to get all the consumers of moderate power. Above a fixed amount the special contract, generally undesirable, may become useful.

After the maximum output comes near to the capacity of the plant, the total yearly output for the given plant is difficult to increase. Hence it is desirable persistently to cultivate the use of power at such times as will not increase the maximum load. This can best be done by offering liberal discounts for power used only between say 6 P. M. and 8 A. M. There is at best rather a small amount of this, and it is all worth getting even at a low rate.

In stations using rented water power at a fixed price per HP, or employing steam, the operating expense is of course variable, and this variation will influence greatly the adjustment of prices, although the general principles are unchanged.

Experience has now shown that electric power transmission may generally be made a profitable enterprise.

If a transmission is planned and executed on sound business principles and with ordinary forethought, it is well-nigh certain to be a permanent and profitable investment.

Failure is generally chargeable to attempts to work with altogether insufficient capital, leading to ruinous actual rates of interest, the purchase of material at extortionate prices due to various forms of credit, and huge commissions to promotors.

Organized in such wise almost any enterprise becomes merely speculative, and its failure should produce neither surprise nor sympathy, for such a course is the broad highway that leads straight into the ever ready clutches of a receiver. Honesty is the best policy in power transmission, as elsewhere.

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